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Initiating a used cooking oil collection network: An SCP–TSP approach within the circular economy framework

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ABSTRACT

Used cooking oil (UCO) management is a critical challenge in advancing circular economy practices. While UCO poses environmental risks, it also offers economic potential, yet collection systems remain inefficient. This study introduces a spatially optimized network model focusing on distance efficiency and service coverage. The Set Covering Problem (SCP) was applied to determine optimal collection points, while the Traveling Salesman Problem (TSP) was used to design transportation routes to centralized facilities. Data from 101 food service businesses in Bantul, with 28 willing to serve as candidate sites, were analyzed. SCP results identified 12 optimal points covering all sources within a 5 km radius. TSP application with two alternative centers produced efficient routes: BUMDes Panggung Lestari (95.7 km; IDR 76,560) and DLH Bantul (95.4 km; IDR 76,320). These findings highlight the effectiveness of SCP–TSP integration in reducing costs and expanding coverage. The novelty lies in combining SCP and TSP within a single framework using district-level empirical data, bridging national circular economy policy with local implementation. This study provides practical guidance for sustainable UCO collection and supports circular economy strategies through resource recovery, while theoretically enriching discourse by demonstrating how SCP–TSP integration operationalizes resource recovery in quantitative terms.

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1. INTRODUCTION

The management of used cooking oil (UCO) from the food service sector in Indonesia remains a strategic issue in the context of waste and sustainability. Improper disposal of UCO poses serious environmental risks, including groundwater contamination and public health hazards [1]. At the same time, UCO holds significant economic and ecological value as a feedstock for biodiesel and other high-value industrial products [2], [3]. This situation highlights a clear gap between the ideal potential of UCO within the framework of the circular economy (CE) and the current practices, which remain unstructured and inefficient. Although the National

Circular Economy Roadmap of Indonesia 2025–2045 identifies waste management as a priority sector, it does not specifically regulate UCO collection systems [1], [4].

Recent studies have attempted to address this challenge through spatial and logistics optimization approaches. Hartini et al. [5] applied the Maximal Covering Location Problem (MCLP) to design UCO collection points in Semarang, while Puspita et al. [6] employed the Set Covering Problem (SCP) to identify optimal locations for Temporary Disposal Sites in South Sumatra. In terms of transportation, Fernandez et al. [7] and Ramos et al. [8] utilized the Vehicle Routing Problem (VRP) for efficient UCO collection routes, whereas Abbas & Benno [9] applied the Traveling Salesman Problem (TSP) to municipal waste collection in Makassar. Other studies also demonstrate the relevance of spatial optimization in waste management, such as Octarina et al. [10] with Robust SCP for temporary waste storage facilities, and Herrera et al. [11] who developed heuristic procedures for urban waste collection routing. Rodríguez et al. [12] further examined the UCO supply chain in Bogotá using genetic algorithms to reduce CO_2 emissions, travel distance, and operational costs.

Taken together, these approaches highlight both the diversity and limitations of existing optimization methods. MCLP emphasizes maximizing service coverage but often overlooks routing efficiency, while VRP focuses on minimizing travel distance yet does not address facility location decisions. SCP, in contrast, provides systematic identification of collection points but requires integration with routing models such as TSP to achieve comprehensive solutions. Collectively, these findings affirm that combining spatial optimization with circular economy principles can enhance logistics efficiency and sustainability. However, most prior studies remain descriptive and treat location or routing separately. In contrast, the present research integrates SCP and TSP within a single framework and connects the optimization results to circular economy principles, thereby offering clearer methodological and theoretical contributions beyond prior works.

Nevertheless, several knowledge gaps remain in used cooking oil (UCO) management in Indonesia. The application of spatial optimization methods such as Set Covering Problem (SCP) and Traveling Salesman Problem (TSP) to UCO management is still limited and unsystematic, despite their proven effectiveness in other waste contexts [13], [14]. Participation of food service enterprises, which are the primary sources of UCO, remains suboptimal, even though their accessibility and willingness are critical to the success of collection systems [15]–[17]. Moreover, no integrative model has yet been developed to simultaneously determine collection point locations and transportation routes based on local data. These gaps underscore the need for a new approach that is adaptive to social, technical, and institutional conditions at the district level, while positioning food service enterprises as active stakeholders in structured collection systems and sustainable resource recovery.

To address these gaps, this study embeds the integration of SCP and TSP within a circular economy framework [2], [18], [19] operationalized through reverse logistics systems that recover UCO into biodiesel or other value-added products. By structuring collection points with SCP and optimizing transportation routes with TSP the system transforms UCO from an environmental burden into a valuable resource [11], [13]. The novelty of this research lies not merely in combining SCP and TSP, but in embedding this integration within circular economy principles and validating it with empirical district-level data. Unlike previous logistics optimization studies that treated location and routing separately or lacked policy relevance, this study bridges national circular economy strategies with local implementation, thereby offering a replicable and policy-oriented solution for sustainable UCO management.

Accordingly, the objective of this research is to design a spatially optimized system for UCO collection and transportation, focusing on food service businesses in Bantul District. The proposed model is expected to serve as a technical recommendation for local governments and food service enterprises, while simultaneously supporting the implementation of the Indonesian Circular Economy Roadmap 2025–2045 and ensuring the sustainability of UCO management.

2. MATERIALS AND METHODS

This study employed a quantitative approach based on mathematical optimization to design a UCO collection system in Bantul Regency. Data on UCO source locations were obtained from Gunawan [20] which contained the names and addresses of the participating food service enterprises. The geographical coordinates of each enterprise were subsequently identified using Google Maps by searching the recorded business name and address. To validate the coordinates, each mapped point was cross-checked against the corresponding street address, village, and district information in the original dataset. Locations with incomplete, duplicate, or inconsistent information were rechecked using alternative business-name and address combinations before being included in the analysis. The validated coordinates were then used to construct the coverage and distance matrices required for the SCP and TSP models. The potential final collection centers were identified through interviews with representatives of BUMDes Panggung Lestari and the Environmental Agency (Dinas Lingkungan Hidup) of Bantul Regency.

The collection network was developed as a two-stage optimization problem consisting of collection-point selection and route determination. The Set Covering Problem (SCP) was used in the first stage because the objective was to determine the minimum number of collection points required to cover all identified UCO sources within the specified 5 km service radius. The model was developed under the assumptions that: (1) all identified UCO sources must be covered by at least one collection point; (2) candidate facilities were limited to the 28 food service enterprises that had expressed willingness to serve as collection points; (3) a UCO source was considered covered when its distance from a candidate facility did not exceed 5 km; (4) each candidate facility was assumed to have sufficient storage capacity during the initial planning period; and (5) overlapping service coverage was permitted because a UCO source could be located within the service radius of more than one collection point.

After the collection points were selected, the Traveling Salesman Problem (TSP) was applied to determine the minimum-distance collection route. The routing model assumed that: (1) one vehicle completed each collection cycle; (2) the route started and ended at the same designated collection center; (3) every selected collection point was visited exactly once during a collection cycle; (4) vehicle capacity was assumed to be sufficient and therefore did not constitute a binding constraint; (5) collection time windows and service-time differences were not considered; (6) traffic and road conditions were assumed to remain constant during the collection cycle; and (7) transportation costs were assumed to vary proportionally with route distance. These assumptions correspond to a basic single-vehicle and single-route collection problem, making TSP suitable.

Therefore, the sequential application of SCP and TSP was considered appropriate for the initial design of the UCO collection network examined in this study. Both models were implemented and optimized using Microsoft Excel Solver. The outputs analysed included the number and location of selected collection points, the minimum route distance for each alternative collection center, and the corresponding estimated fuel costs.

2.1. Set Covering Problem (SCP)

SCP is one of the methods that can be used to determine the minimum number of facilities and to assign demand points so that they are covered by at least one facility [21]. The objective of the set covering model is to minimize the number of facility locations while ensuring that all demand points are adequately served [22]. The formulation of this model can be expressed as follows:
Objective function, used to minimize the number of facility locations.

$$Min \sum_{j \in i} x_j \tag{1}$$

Constraint function, that ensures each demand point is covered by at least one facility and each demand point must be served by at least one facility location.

$$\sum_{j \in i} a_{ij} x_j \geq 1 \qquad i = 1,2, \ldots, n \tag{2}$$

Decision variable,

$$x_j = \begin{cases} 1, & if\ facility\ location\ j\ is\ selected \\ 0, & otherwise \end{cases} \tag{3}$$

$$a_{ij} = \begin{cases} 1, & if\ demand\ point\ i\ is\ covered\ by\ facility\ location\ j \\ 0, & otherwise \end{cases} \tag{4}$$

where,
i = demand point
j = facility location
x_j = decision variable

a_{ij} = coverage coefficient indicating whether demand point *i* is covered by facility *j*

2.2. Traveling Salesman Problem (TSP)

TSP is a well-established combinatorial optimization approach used to determine the shortest possible route that visits a set of nodes exactly once and returns to the origin point. The primary objective of the TSP is to minimize the total travel distance or transportation cost while ensuring that each demand point is served within a single tour [23].

In the context of this study, the TSP model is employed to optimize the route for collecting UCO from multiple collection points to a designated collection center. Each collection point is represented as a node in the network, while the collection center serves as both the starting and ending point of the route. The model ensures that all nodes are visited exactly once, forming a closed-loop route that minimizes the total travel distance.

Mathematically, the TSP can be formulated as a minimization problem, where the objective function seeks to minimize the total distance between nodes, subject to constraints that enforce route continuity and prevent sub-tours [23], [24]. This ensures that the resulting solution represents a feasible and efficient route covering all collection points as shown below:
Objective function : minimize total distance.

$$Min\ Z = \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}X_{ij} \tag{5}$$

Constraint that ensures each node is connected to exactly one other node is expressed as:

$$\sum_{j=1}^{n} X_{ij} = 1, \qquad j = 1,2,\dots,n \tag{6}$$

Constraint that ensures each node is visited from exactly one other node is expressed as:

$$\sum_{i=1}^{n} X_{ij} = 1, \quad i = 1,2,\dots,n \tag{7}$$

Constraint that ensures each node is visited only once is defined as:

$$X_{ij} \in \{0,1\}, \qquad i,j = 1,2,\dots,n \tag{8}$$

where,
C_{ij} = distance from node *i* to node *j*
X_{ij} = binary decision variable, equal to 1 if the route node *i* to node *j* is selected, and 0 otherwise
n = total number of nodes to be visited
i,j = indices representing the nodes
Z = total travel distance

The application of TSP in waste collection and reverse logistics systems has been widely adopted due to its effectiveness in reducing operational costs and improving transportation efficiency. Previous studies have demonstrated that route optimization using TSP and its variants can significantly reduce travel distance and fuel consumption in waste collection systems [25], [26]. Therefore, the use of TSP in this study provides a systematic and efficient approach to designing the UCO collection route under the given spatial conditions.

3. RESULTS

3.1. Food service Industries location

A total of 101 food service businesses were examined, with their geographical coordinates determined using Google Maps and presented in **Figure 1**. Among these, 28 food service businesses agreed to serve as collection points for used cooking oil, indicated by yellow markers.

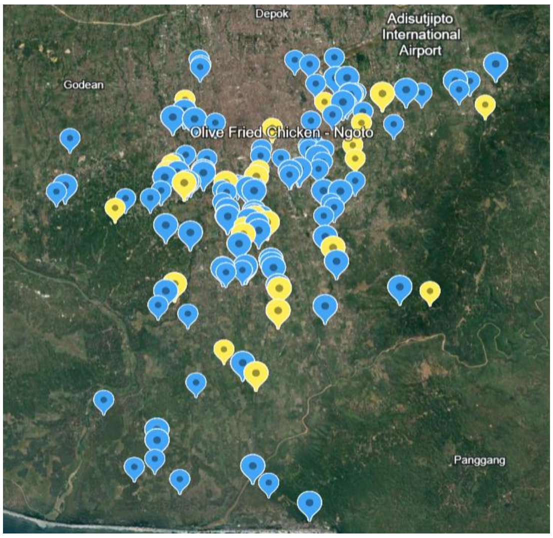

Figure 1. Locations of the food service businesses under study

As illustrated in Figure 1, the food service enterprises are not uniformly distributed across the study area. A relatively high concentration is visible in the central and northern parts of Bantul, particularly in areas adjacent to Yogyakarta City, whereas the southern and eastern parts contain more dispersed sources. The 28 candidate collection points are distributed across these spatial clusters, but their availability does not fully correspond to the density of UCO sources in every area. This uneven spatial pattern justifies the use of a location-allocation model, because selecting collection points solely on the basis of visual proximity could result in redundant facilities in densely populated areas while leaving geographically isolated sources insufficiently served.

Twenty-eight food service businesses that agreed to serve as collection points were designated as candidate sites. Table 1 shows that the candidate collection points are located in several districts with different spatial characteristics. A substantial proportion of the candidates is concentrated in Banguntapan, Sewon, and Kasihan, where food service activities are relatively dense. In contrast, only a limited number of candidates are available in more peripheral districts, such as Dlingo, Pundong, Piyungan, Bambanglipuro, and Pandak. Consequently, the candidate set contains both closely located alternatives in the central part of the study area and isolated facilities that are strategically important for covering distant UCO sources. This distribution indicates that the selection decision should consider not only the number of businesses located near each candidate but also the contribution of individual candidates to maintaining complete territorial coverage. It should also be emphasized that the candidate locations were restricted to enterprises that had expressed willingness to participate; therefore, Table 1 represents a socially feasible candidate set rather than all geographically possible facility locations.

Table 1. Candidate collection points

Food Service Industry as Candidate Collection Points	Code	Address (Village, District)
RMPB	6	Trimulyo, Kec. Jetis
AGS	12	Banguntapan, Kec. Banguntapan
PIR	17	Jambidan, Kec. Banguntapan
PK	22	Potorono, Kec. Banguntapan
KLM	25	Banguntapan, Kec. Banguntapan
WOS	41	Timbulharjo, Kec. Sewon
FR	43	Bangunharjo, Kec. Bantul
RMRR	46	Panggungharjo, Kec. Sewon
JR	49	Pendowoharjo, Sewon
DG	51	Pendowoharjo, Kec. Sewon

Food Service Industry as Candidate Collection Points	Code	Address (Village, District)
S	61	Timbulharjo, Kec. Sewon
PT	62	Timbulharjo, Sewon,
RMPM	67	Panggungharjo, Kec. Sewon
PSR	74	Ngestiharjo, Kec. Kasihan
LJR	75	Jetis, Tamantirto, Kec. Kasihan
BC	77	Bangunjiwo, Kasihan
KLA	79	Bangunjiwo, Kec. Kasihan
WSS	92	Tirtonirmolo, Kec. Sewon
DIC	97	Ngestiharjo, Kec. Kasihan
WT	101	Bangunjiwo, Kec. Kasihan
PMP	104	Sumbermulyo, Kec. Bambanglipuro
GDMS	106	Mangunan, Kec. Dlingo
MLMP	110	Patalan, Kec. Jetis
KC	112	Jetis, Patalan, Kec. Jetis,
RMSS	124	Gilangharjo, Kec. Pandak
LC	125	Sendangtirto, Kec. Berbah
BIR	126	Srimulyo, Kec. Piyungan
SR	140	Panjangrejo, Kec. Pundong

3.2. Determination of Collection Points Using the SCP Method

The locations and number of collection points were determined from 28 candidate sites using the Set Covering Problem (SCP) formulation presented in Eqs. (1)–(4) and implemented in Microsoft Excel Solver, as illustrated in Figure 2. Each candidate location was represented by a binary decision variable, with a value of one indicating selection and zero otherwise. The objective function minimized the total number of selected collection points, subject to the requirement that all 101 food service enterprises be covered by at least one facility within a 5 km radius. Because both the objective function and coverage constraints were linear, the model was solved using the Simplex LP method with binary restrictions. The optimization evaluated alternative combinations of candidate sites and identified a minimum set of 12 collection points that satisfied the coverage requirements while incorporating stakeholder willingness. The Solver configuration shown in Figure 2 links the mathematical formulation directly to its computational implementation and enhances the reproducibility of the analysis.

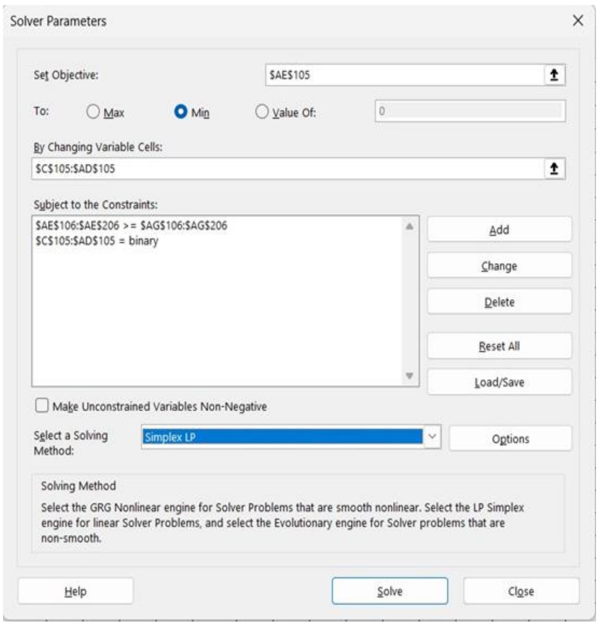

Figure 2. Screenshot of the solver for SCP

Based on the calculations performed using Microsoft Excel Solver, the output identified 12 selected collection points. The 5 km coverage radius applied in the SCP model was determined based on responses from food service enterprises participating in the survey. When asked about the maximum distance they were still willing to travel to deliver used cooking oil to a designated collection point, the majority indicated a threshold of approximately 5 km. This empirical input was therefore adopted as a practical constraint in the optimization process, ensuring that the selected collection points reflect both operational feasibility and stakeholder acceptance. The chosen collection points, along with the coverage of the food service industry they serve, are presented in Table 2.

Table 2. Selected collection points and their service coverage

No	Selected Collection Points	Address	Covered Food Service Industry
1	RMPB	Trimulyo, Kec. Jetis	2,6,20,108,113,136
2	AGS	Banguntapan, Kec. Banguntapan	1,12,14,15,17,22,23,24,25,28,29,30,32,33,34,35,36,37, 39,125,127,129,136
3	KLM	Banguntapan, Kec. Banguntapan	12,14,15,17,18,22,23,25,28,29,32,33,34,35,36,39,125
4	S	Timbulharjo, Kec. Sewon	2,4,7,8,9,10,40,41,43,45,46,47,48,49,50,51,52,54,56,57 ,58,59,60,61,62,65,67,69,70,71,72,89,92,112,118,136
5	RMPM	Panggungharjo, Kec. Sewon	1,10,16,24,26,37,40,41,43,45,46,47,48,49,50,51,52,54, 56,57,58,59,60,61,62,65,67,69,70,71,72,89,92
6	BC	Bangunjiwo, Kasihan	70,73,74,75,76,77,79,80,81,84,87,90,92,93,94,100,101, 102,118
7	DIC	Ngestiharjo, Kec. Kasihan	74,82,83,84,87,97,98
8	PMP	Sumbermulyo, Kec. Bambanglipuro	103,104,105,140,141
9	GDMS	Mangunan, Kec. Dlingo	106,107
10	RMSS	Gilangharjo, Kec. Pandak,	4,7,8,9,121,124
11	BIR	Srimulyo, Kec. Piyungan,	126,128,132,133
12	SR	Panjangrejo, Kec. Pundong	104,105,110,111,140,143

As shown in Table 2, the 12 selected collection points collectively cover all 101 food service enterprises, although their individual contributions vary considerably. Point S provides the broadest coverage by serving 36 enterprises, followed by RMPM with 33 enterprises and AGS with 23 enterprises, whereas GDMS covers only two enterprises. Despite its limited numerical coverage, GDMS remains essential because it serves geographically isolated sources that cannot be adequately reached by other selected points within the specified 5 km radius, illustrating that the SCP model may retain a facility with limited demand when it is critical to ensuring complete spatial coverage. Overall, the coverage lists contain 164 source-to-facility relationships, equivalent to an average of approximately 1.62 feasible collection points per enterprise, confirming the presence of overlapping service areas. This overlap was intentionally permitted because the 5 km radius represents the maximum distance that participating enterprises were willing to travel and provides flexibility when the nearest facility is temporarily unavailable or reaches its storage capacity. The overlap also reflects the spatial clustering of the network, as AGS and KLM serve many of the same enterprises in Banguntapan, while S and RMPM share substantial coverage in Sewon and surrounding areas. In contrast, PMP, GDMS, BIR, and SR primarily serve more peripheral locations. Therefore, the selected configuration combines high-coverage central facilities with strategically positioned peripheral points, balancing operational consolidation, territorial reach, and network resilience. Nevertheless, formal assignment and coordination are required to prevent duplicate reporting, irregular deliveries, and unequal UCO distribution, while the subsequent TSP optimization organizes the selected points into an efficient collection route.

3.3. Route Optimization for UCO Collection Using the TSP Method

In the subsequent stage of research, two locations were identified as potential final collection centers for UCO, namely *BUMDes Panggung Lestari* and the Environmental Agency of Bantul Regency. Based on these findings, two transportation route scenarios were developed from the collection points to the designated collection centers. The first scenario considers *BUMDes Panggung Lestari* as the collection center, while the second scenario designates the Environmental Agency of Bantul Regency as the collection center.

The transportation routes were determined using the Traveling Salesman Problem (TSP), with optimization performed through Microsoft Excel Solver, as illustrated in Figure 3. Although Eqs.(5)–(8) present the conventional binary arc-based formulation, in which decision variables indicate whether a connection between two nodes is selected, the spreadsheet model adopted an integer permutation encoding as a practical computational representation. Each decision cell specified the visiting order of one of the 12 collection points selected by the SCP model, with integer values restricted from 1 to 12. The "AllDifferent" constraint ensured that each position in the route sequence was assigned only once, thereby preventing duplicate visits and ensuring that all collection points were included in a single tour. The objective cell calculated the total distance associated with the resulting sequence, including the return trip to the designated collection center, and was minimized using the Evolutionary algorithm. Through iterative evaluation of alternative route permutations, Solver identified the sequence with the lowest total travel distance. Thus, despite differences in decision-variable structure, both the mathematical formulation and the spreadsheet implementation pursue the same objective: generating a closed route that visits every selected collection point exactly once while minimizing total transportation distance.

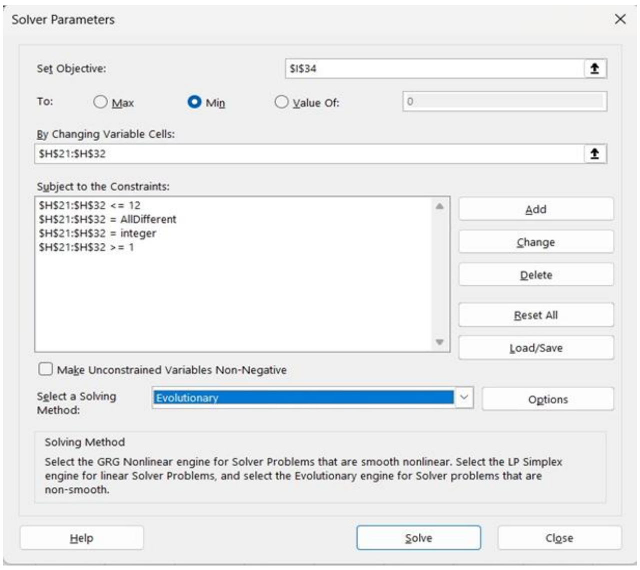

Figure 3. Screenshot of the solver for TSP

The transportation routes optimized using the TSP method for the two alternative collection centers: BUMDes Panggung Lestari in scenario (a) and the Environmental Agency of Bantul Regency in scenario (b) are presented in Figure 4. Because both scenarios require visits to the same 12 collection points, most major route segments are similar, while the principal differences occur in the initial and final portions of the tours due to the change in origin and destination. Relatively long movements toward the eastern and southern parts of the study area remain necessary in both scenarios because several collection points are located in peripheral areas, thereby contributing substantially to the total route distance. The route patterns also indicate that the TSP optimization connects geographically adjacent points sequentially wherever possible, reducing unnecessary backtracking and improving travel efficiency. However, some longer connecting segments cannot be eliminated because the SCP model prioritizes complete spatial coverage and therefore retains strategically important peripheral facilities. Consequently, relocating the collection center within the central part of the network results in only a limited reduction in overall distance. This outcome demonstrates the complementary roles of the two optimization stages: the SCP model ensures that all UCO sources are adequately covered, while the TSP model minimizes the transportation burden associated with visiting the selected collection points.

The total minimal distances of each transportation route are summarized in Table 3. When BUMDes Panggung Lestari is designated as the collection center, the total route distance is 95.7 km, whereas the designation of the Environmental Agency of Bantul Regency as the collection center results in a total minimal route distance of 95.4 km. Assuming a fuel cost of IDR 10,000 per litre, the total transportation cost for each scenario amounts to IDR 76,560 and IDR 76,320, respectively. Because the cost difference is marginal, Table 3 suggests that route distance should not be the sole criterion for selecting the final collection center. Factors such as available storage capacity, operating hours, personnel, vehicle availability, road accessibility, institutional responsibility, and proximity to downstream UCO processors may have a greater influence on implementation feasibility than the IDR 240 difference in fuel cost.

Transportation costs in this study were estimated based on the assumed fuel consumption of standard light-duty vehicles commonly used by food service enterprises. The model adopted an average fuel consumption rate of 0.08 liters per kilometer, derived from local survey data and manufacturer specifications [27], which indicate that one liter of fuel enables an average travel distance of 12.5 kilometers. This assumption was further combined with prevailing fuel prices during the study period. This assumption provided a consistent basis for calculating route costs in the TSP optimization, ensuring that the results reflect realistic operating conditions while remaining adaptable to future changes in fuel efficiency or price levels.

Although the distance difference between the two scenarios is numerically small, its operational significance lies in cumulative effects. Even marginal reductions in travel distance can translate into measurable savings in fuel consumption, transportation costs, and emissions when routes are repeated regularly. Moreover, shorter routes reduce driver workload and improve reliability of collection schedules. Thus, while the numerical gap may appear limited, its practical implications for efficiency and sustainability remain relevant.

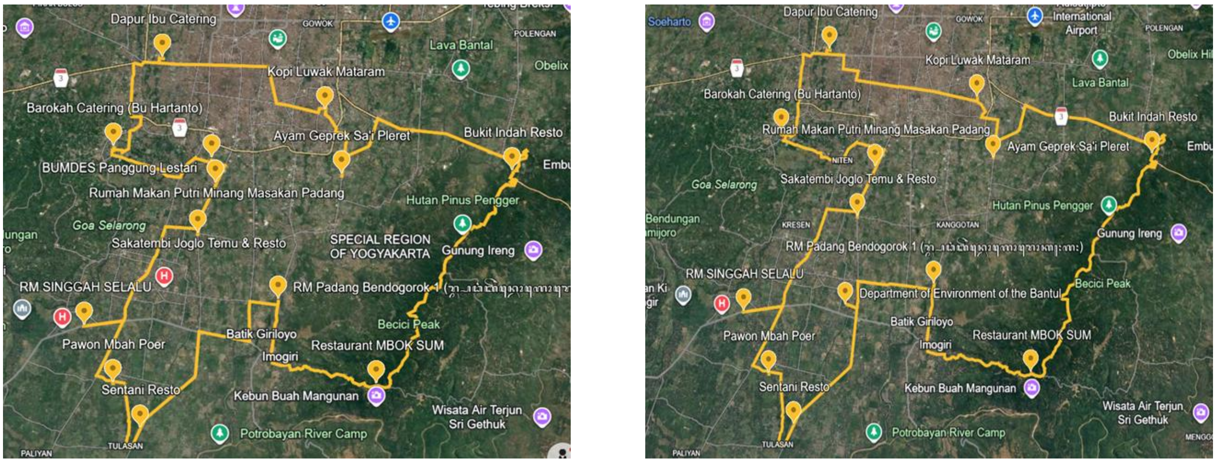

Figure 4. transportation routes for UCO based on TSP (a) BUMDeS panggung lestari as the collection center (b) The environmental agency of Bantul regency as the collection center

Table 3. Post-optimization outcomes for scenarios (a) and (b)

Collection Center	Route Distance (km)	Estimated Fuel Cost (IDR)
BUMDes	95.7	76,560
Environmental Agency	95.4	76,320

This analysis was conducted under baseline assumptions regarding fuel prices and coverage radius to ensure clarity and comparability of results. It is acknowledged that variations in these parameters may affect both cost efficiency and spatial feasibility. As part of a basic sensitivity analysis, changes in fuel prices per liter directly alter transportation costs. The impacts of fuel price increases on transportation expenses are presented in Table 4.

Table 4. Basic sensitivity analysis due to changes in fuel prices per liter

Collection Center	Route Distance (km)	Fuel Price Increase (%)	Price in IDR	Estimated Fuel Cost (IDR)
BUMDes	95.7	10	11,000	84,216
		20	12,000	91,872
Environmental Agency	95.4	10	11,000	83,952
		20	12,000	91,584

The sensitivity analysis presented in Table 4 demonstrates the direct relationship between fuel price fluctuations and transportation costs within the UCO collection network. Under baseline conditions, the model assumed stable fuel prices; however, incremental increases of 10% and 20% reveal proportional rises in estimated fuel expenditures. For the BUMDes route (95.7 km), costs increased from IDR 76,560 at baseline to IDR 84,216 (+10%) and IDR 91,872 (+20%). Similarly, the Environmental Agency route (95.4 km) showed increases from IDR 76,320 to IDR 83,952 (+10%) and IDR 91,584 (+20%).

These results highlight that transportation costs are highly sensitive to fuel price changes, with even modest adjustments exerting measurable impacts on overall efficiency. While route distances remain constant, the financial burden escalates in line with fuel price volatility, underscoring the importance of incorporating dynamic fuel pricing into operational planning. From a policy perspective, this sensitivity analysis emphasizes the need for adaptive budgeting and potential integration of alternative energy or efficiency measures to mitigate risks associated with fuel price instability.

Adjusting the coverage radius would provide deeper insights into the robustness of the proposed model, as variations in spatial parameters could reveal how sensitive the system is to changes in service reach and logistical constraints. Although such extensions lie beyond the scope of this paper, they represent a promising avenue for future research that could enhance operational relevance and strengthen the applicability of circular economy policies at both local and regional levels.

4. DISCUSSION

The findings demonstrate that the sequential application of the Set Covering Problem (SCP) and Traveling Salesman Problem (TSP) can support the design of an efficient district-level UCO collection network. The SCP model selected 12 collection points from 28 candidate locations while maintaining coverage within the specified 5 km radius, and the TSP model subsequently generated minimum distance routes to two alternative collection centers. These results are consistent with previous studies showing that spatial optimization can improve facility location and waste collection routing [5], [7], [9], [12].

The contribution of this study lies in applying SCP and TSP within a single empirically grounded framework that incorporates the willingness of food service enterprises to serve as collection points. Of the 101 enterprises considered, only 28 were willing to participate, indicating that feasible network design depends not only on spatial proximity but also on stakeholder acceptance. This finding supports Budijati et al. [15]–[17], who emphasized willingness and accessibility as important determinants of UCO collection participation.

From a circular economy perspective, the proposed framework provides a practical mechanism for organizing the reverse flow of UCO from waste generators to collection centers and downstream recovery activities. SCP and TSP translate the principles of resource recovery and waste valorization into location and routing decisions [19]. However, the optimization model represents only the logistical foundation of the collection system, as effective implementation also requires sustained participation, institutional coordination, quality control, and reliable connections with UCO processors.

Practically, the comparison between BUMDes Panggung Lestari and environmental agency Bantul indicates that the two alternative collection centers produce nearly identical transportation outcomes, with route distances of 95.7 km and 95.4 km, respectively. The difference of only 0.3 km is unlikely to be operationally significant when considered solely in terms of fuel cost. Therefore, the selection of a collection center should not be based exclusively on route distance, but should also consider storage capacity, vehicle and personnel availability, operating schedules, accessibility, administrative authority, and proximity to downstream UCO processors.

Implementing the proposed network may also face several practical challenges. The selected food service enterprises must remain willing to provide storage space and assume additional responsibilities related to UCO handling, record keeping, and quality control. Variations in collection volume, contamination by water or food residues, irregular collection frequency, and limited coordination among participants may reduce operational efficiency. Moreover, the estimated transportation cost includes only fuel expenditure and does not account for labour, containers, loading and unloading, vehicle maintenance, storage facilities, monitoring, or administrative costs. Consequently, the proposed model should be regarded as an initial decision-support tool whose practical feasibility must be validated through stakeholder agreements, more comprehensive cost analysis, and pilot implementation.

Overall, this study contributes both theoretically and practically to the advancement of circular economy strategies. It demonstrates that mathematical optimization can transform UCO from an environmental liability into a valuable resource, while also providing actionable insights for policymakers, municipal agencies, and community enterprises. By aligning operational efficiency with sustainability objectives, the proposed model offers a replicable pathway for developing countries where structured waste collection systems remain limited.

The proposed SCP–TSP framework has potential application beyond Bantul Regency, but its scalability depends on the spatial, infrastructural, operational, and institutional characteristics of the target region. Its transferability should therefore be understood as the adaptation of an analytical procedure rather than the direct replication of the current model parameters. In particular, the 5 km coverage radius used in this study was derived from the stated willingness of food service enterprises in Bantul and should be locally validated before being applied elsewhere.

In densely populated urban areas, shorter service radii may be sufficient because UCO sources are geographically concentrated, although congestion, parking restrictions, narrow roads, and limited operating hours may require more complex routing constraints. In rural or mountainous regions, wider coverage areas may be necessary because sources are more dispersed, while road quality, terrain, and limited transportation infrastructure may increase collection costs. Coastal or archipelagic regions may require intermediate storage facilities, multiple collection centers, or multimodal transportation. Moreover, as network size and operational complexity increase, the basic SCP–TSP formulation may need to be replaced or extended by capacitated facility-location models, Vehicle Routing Problem variants, multi-depot routing, or integrated location-routing models.

Scaling the framework also requires strong stakeholder coordination and adequate institutional readiness. Local governments, BUMDes, food service enterprises, transport operators, UCO traders, and downstream processors must have clearly defined roles and responsibilities. A coordinating institution is needed to manage collection schedules, data reporting, storage standards, quality control, cost allocation, and agreements with downstream processors. Formal arrangements, such as memoranda of understanding or operating contracts, can help maintain stakeholder commitment and clarify the distribution of costs, revenues, and operational risks.

Institutional capacity may become a major constraint when local authorities or community organizations lack dedicated personnel, vehicles, storage facilities, monitoring systems, operational budgets, or legal authority. Therefore, replication in other regions should be preceded by an assessment of organizational capacity, regulatory support, financial feasibility, and market access for collected UCO. Policy support may include standardized collection procedures, minimum storage and safety requirements, incentive mechanisms for participating enterprises, and an integrated database for monitoring collection volumes and facility performance. Experiences from China, Europe, and Indonesia demonstrate the broader relevance of spatial optimization for UCO and waste collection [2], [5], [28] but they do not imply that a single model configuration or governance arrangement is universally applicable.

This study has several limitations that should be considered when interpreting the results. First, the analysis was based on 101 food service enterprises in Bantul Regency, of which only 28 were willing to serve as candidate collection points. Therefore, the selected network may change if stakeholder participation increases or decreases. Second, the 5 km coverage radius was treated as a fixed parameter based on stated willingness, although actual participation may also be influenced by travel time, road conditions, incentives, and UCO volume. Third, the SCP–TSP model is static and deterministic and does not account for traffic variation, seasonal changes in UCO generation, collection time windows, or uncertainty in business operations. The TSP formulation also assumes a single route without explicitly considering vehicle capacity, multiple vehicles, collection frequency, service time, or differences in UCO volume among collection points. In addition, the transportation-cost estimate includes only fuel expenditure and excludes labour, vehicle depreciation, maintenance, storage, handling, and administrative costs. Finally, no sensitivity analysis was conducted for alternative coverage radii, fuel prices, stakeholder participation rates, or collection-center locations. Future studies should address these limitations through sensitivity analysis, pilot implementation, dynamic demand data, and more advanced capacitated location-routing or vehicle-routing models.

5. CONCLUSION

This study demonstrates that integrating SCP and TSP provides an effective framework for optimizing UCO collection systems. The SCP results identified 12 feasible collection points within a 5 km coverage radius, reflecting the operational preferences of food service enterprises. The subsequent TSP optimization produced two alternative scenarios: BUMDes Panggung Lestari with a total route distance of 95.7 km and transportation cost of IDR 76,560, and DLH Bantul with a route distance of 95.4 km and cost of IDR 76,320. Although the numerical difference between the two scenarios is relatively small, it shows that even marginal variations in route length can yield cumulative savings in fuel use and expenses when applied repeatedly. Together, these outcomes confirm that the integrated SCP–TSP model reduces operational costs while ensuring comprehensive service coverage, thereby offering a replicable solution for structured UCO collection at the district level.

Practically, the proposed approach provides actionable guidance for local governments and community-based organizations to designate feasible collection points and optimize routing. By embedding optimization results into district-level data, the model supports better resource allocation, lowers operational costs, and strengthens energy and environmental resilience. These findings highlight the dual benefits of environmental protection and economic value recovery, demonstrating how structured UCO management can be directly implemented to advance circular economy strategies at the local scale.

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DECLARATION OF AI-TOOL USAGE

Artificial Intelligence (AI) tools were employed in limited aspects of this manuscript preparation. Specifically, AI assistance was used for:

- Academic paraphrasing and translation: Certain Indonesian research statements and descriptions were paraphrased and translated into plagiarism-free academic English.
- Language refinement: AI support was utilized to improve clarity, conciseness, and academic tone in selected sections of the manuscript.
- Reference exploration: Employed AI-based browsing assistance to identify relevant journal articles for background study.

No AI tools were used in the design of the research, data collection, analysis, or interpretation of results. All substantive research activities and critical evaluations were conducted independently by the authors.