# Optimization of Recycling Collection Network for BOI Industrial Zones in Sri Lanka


**A project report presented by:**

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And

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# 1 Abstract

Sri Lanka's rapid industrial development has significantly increased industrial waste generation, particularly within Board of Investment (BOI) zones. Despite the high potential for recycling, inefficient waste collection systems and the absence of centralized processing facilities have led to high transportation costs and poor waste utilization. This study focuses on identifying the optimal location for a centralized waste processing center to enhance recycling efficiency and minimize operational costs. The problem was formulated and solved using the Single Facility Location Model from Operations Research, which determines the most cost-effective point for a single facility serving multiple demand zones. The optimization was conducted using the L-BFGS-B algorithm implemented in Python, allowing precise handling of continuous variables and spatial constraints such as exclusion zones and buffer distances. Real industrial waste data obtained through the Lanka Responsible Care Council ensured model validity. The resulting solution provides a practical and scientifically grounded framework for policymakers and industry stakeholders to establish a sustainable, cost-efficient waste management system across Sri Lanka's industrial zones.

## 2 Acknowledgment

We express our sincere gratitude to all those individuals who assisted us in the completion of our project titled "Optimization of Recycling Collection Network for BOI Industrial Zones in Sri Lanka."

Our heartfelt thanks are due to our departmental supervisor, Mrs. Nirosha Disanayake, for her continuous guidance, encouragement, and invaluable advice throughout this research work. Her expertise, patience, and professionalism were the foundation of our research work, and her supervision encouraged us toward addressing each step of the research work with professional demeanor and academic integrity.

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Our appreciation further extends to Ms. Terancy Samarawickrama, Assistant Director at the Board of Investment (BOI), and Ms. Sukitha Ranasinghe, Assistant Director at the Central Environmental Authority (CEA), for their cooperation and for supplying valuable data and expert advice that contributed to our study.

We extend our sincere gratitude to Eng. Eranga Dilhan, General Manager – Sustainable Business at MAS Holdings; Ms. Leonie Vas, General Manager – Sustainability at Hirdaramani Group; and Mr. Gayan Samarakoon, Manager – Sustainability at Hayleys Group, for their sponsorship, technical support, and commitment to promoting sustainable industrial practices that greatly contributed to the success of our project.

A special word of thanks is provided to Mr. Channa Lakmal, Senior Executive – Sustainability, Hirdaramani Industries Sithro Washing Plant, and Mr. Chamod Wijesingha, Executive – Environmental Sustainability, Hirdaramani Apparel – Seethawaka, for their kind facilitation and coordination of our field visit, which introduced us to first-hand experience of the practical issues associated with recycling and waste management activities.

Finally, we express our sincere gratitude to the academic staff of the Department of Mathematics and the Department Of Statistics And Computer Science, University of Peradeniya, for supervision and encouragement. We also express our special gratitude to our demonstrators, Mr.Thinendra Wijesuriya, Ms.Ranali Piyatilake, Ms.Nipuni Fernando, Ms.Nipuni De Silva and Ms.Buddhini Colombage for guidance, practical tips, and constant encouragement during the project.

# 3 Introduction

## 3.1 Background of the study

Sri Lanka's industrial growth has brought major economic benefits, but it has also led to a steady rise in industrial waste generation. Many recyclable materials in these waste streams are not properly collected or processed, which increases transportation and operational costs while causing environmental issues. The Board of Investment (BOI) currently manages 12 main industrial zones across the country. From these, a few zones were selected for this study to analyze waste generation patterns and optimize the recycling collection process. To address the inefficiencies in the current system, this project focuses on identifying the best location for a centralized waste processing center. Establishing such a facility would improve recycling efficiency, reduce transport distances and costs, and support more sustainable industrial operations in Sri Lanka.

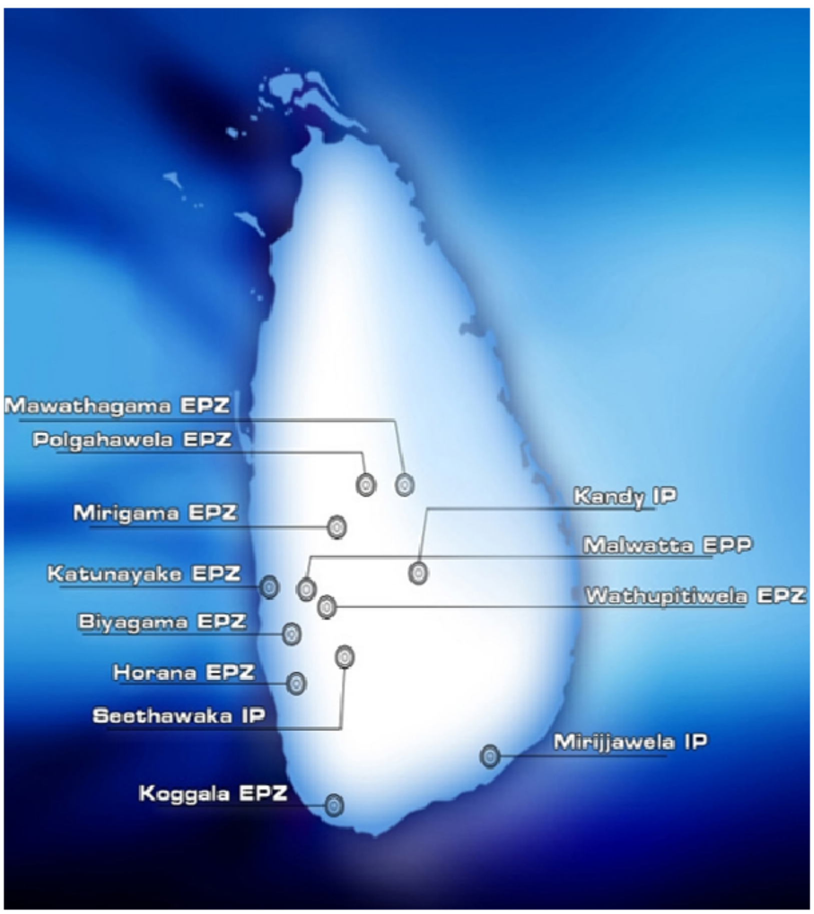



Figure 1: 12 BOI Zones in Sri Lanka

### 3.2 Problem Statement

The recycling system in industrial zones is currently fragmented, with no central processing facility. This causes high transportation cost, operational cost and many recyclable materials are underutilized. The main challenge of this project is to find the optimal location for a centralized waste processing center that can minimize costs and improve recycling efficiency.

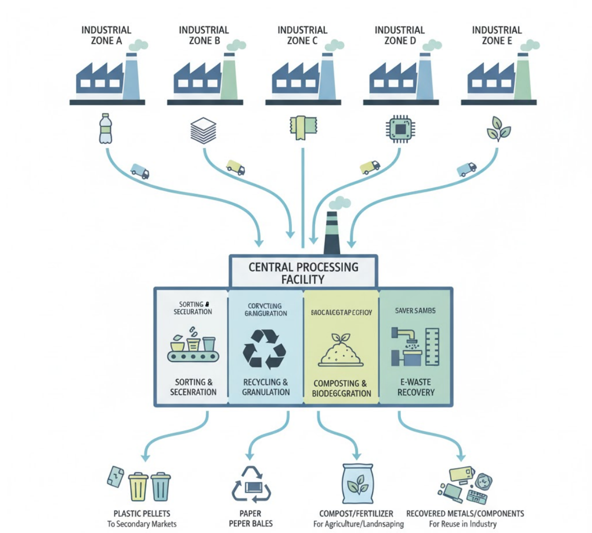



Figure 2: Conceptual Sketch of problem statement

### 3.3 Collaboration with Stakeholders

This project is supported by the Lanka Responsible Care Council (LRCC), a registered institute in Sri Lanka promoting the Responsible Care concept, a global program aimed at enhancing environmental, health and safety performance in industries and it is managed by International Council of Chemical Association (ICCA), USA. Lanka Responsible Care Council confirmed the project and provided access to industrial data, ensuring this study addresses a real industrial problem. Dr.Lakmini Edirisinghe, CEO,LRCC, acts as the council's contact for this project.

Figure 3: Logos of ICCA and LRCC

Additional collaborators include:

- Board of Investment (BOI) – Ms. Terancy Samarawickrama, Assistant Director

Figure 4: Logo Of CEA

- Central Environmental Authority (CEA) – Ms. Sukitha Ranasinghe, Assistant Director

Figure 5: Logo Of BOI

Key industry partners in the BOI zones also provided support and insights:

- MAS Holdings – Eng. Eranga Dilhan, General Manager – Sustainable Business

Figure 6: Logo Of MAS Holdings

- Hirdaramani Group – Ms. Leonie Vas, General Manager – Sustainability

Figure 7: Logo Of MAS Hirdaramani Group

- Hayleys Group – Mr. Gayan Samarakoon, Manager – Sustainability

Figure 8: Logo Of Hayleys Group

These partnerships enhance the study by providing practical support, reliable data and industry perspectives, ensuring the project outcomes are applicable in real industrial settings.

Figure 9: Feild Visit : Seethawaka BOI Zone

### 3.4 Problem Confirmation and Official Communication

The Lanka Responsible Care Council officially endorsed this project through formal letters that outline the research problem and collaboration framework. These documents confirm the industrial relevance of the issue, ensure access to accurate waste data from the BOI zones, and provide guidance on the project's focus areas and selected waste types.

Copies of these official letters are included in Appendix A and Appendix B for reference.

Appendix A: Lanka Responsible Care Council Official Letter of Problem Confirmation

Appendix B: Lanka Responsible Care Council Official Collaboration and Guidance Letter

### 3.5 Significance of the Study

This project addresses critical industrial challenges while promoting sustainable practices. By identifying the optimal location for centralized waste processing center, the project aims to:

- Improve recycling efficiency and reduce waste generation
- Reduce transportation and operational costs.
- Develop a replicable model for other industrial zones in Sri Lanka
- Demonstrate how industry-academic collaboration can create practical solution

## 3.6 Objectives of the Study

The main objectives are:

- To identify the optimal location for a centralized waste processing center.
- To reduce transportation and operational costs using optimization techniques.
- To create a framework that could be applied to other BOI zones in the future.

## 3.7 Scope of the Study

| 5 BOI Zones | 5 Waste Types |
|---|---|
| Katunayake | Plastic |
| Biyagama | Fabric |
| Seethawaka | Biodegradable waste |
| Koggala | Paper |
| Horana | E-waste |

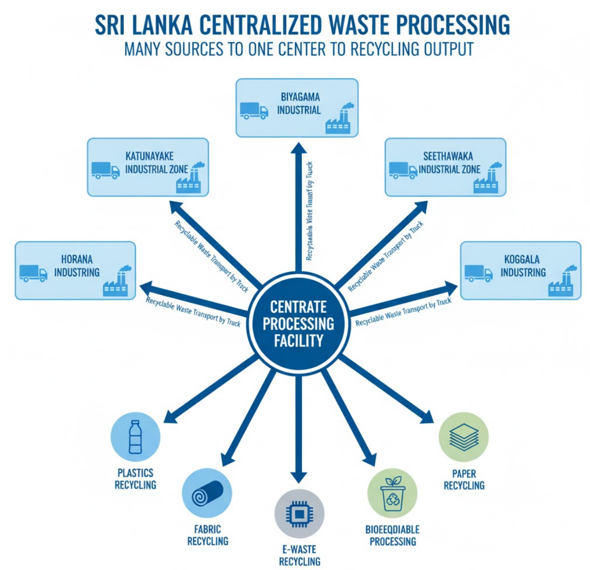



Figure 10: Slope of the Study

All data on waste generation was collected directly from the respective BOI Zones, ensuring accuracy and reliability. The project uses optimization modeling to identify the optimal location for a centralized waste processing center.

# 4 Literature Review

## 4.1 Review - Problem Background

The management of industrial waste in Sri Lanka is under increasing scrutiny due to growing environmental and economic concerns [1]. Despite the presence of recyclable materials in waste streams, recycling efforts remain inefficient, largely due to fragmented operations and prohibitive transportation costs [2]. Most BOI industrial zones are isolated from each other geographically, resulting in limited access to waste collection service providers.Materials that could otherwise be recycled are currently transported long distances for co-processing, such as to the cement kiln in Puttalam [3]. This is both economically and environmentally unsustainable [4]. There is an urgent need for a centralized, optimized system for collection and recycling that minimizes costs while maximizing recovery rates. This research project seeks to develop a transport-optimized model that can guide the establishment of a recycling center in the most strategic location, using a systematic, data-driven approach.

## 4.2 Review - Optimization Models

### 4.2.1 Transportation Model

The Transportation Model is a well-known linear programming method that helps minimize total transportation costs between multiple origins and destinations while meeting supply and demand needs. In waste management, it's often used to figure out the most cost effective routes for moving waste from where it's produced to where it's processed or disposed of. This makes it easier for decision-makers to allocate resources efficiently, ensuring that trucks take the best routes and waste loads are evenly distributed.

[5] For example, Warusavitharana and Ranasinghe (2013) showed how transportation models can optimize waste collection routes in Sri Lanka and lay the groundwork for minimizing transport costs in industrial areas.[6] Murakami et al. (2008) found that adding GIS data to transportation models improves the spatial accuracy of cost estimates, which can really help when modeling BOI waste logistics.[7] Joseph and Gunaratne (2022) used LP based transportation optimization in Ratmalana, Sri Lanka, and managed to cut operational costs; the data structures from their research can be adapted for modeling waste flow in BOI zones.

The transportation model works on the idea that every bit of what's produced (supply) must get delivered somewhere it's needed demands so the total supply and demand are always balanced. Each shipment has a clear, predictable cost, and it's assumed the goods are all the same and can be divided up as needed. There aren't usually limits on how much can travel along each possible route, and you can send shipments from any origin to any destination. Everything about supply, demand, and cost is known upfront, with no surprises along the way.

Unlike the FLP, the transportation model doesn't make you choose where to build or open facilities; it just tells you how to move stuff between places that already exist.

### 4.2.2 Assignment Problem Model

The Assignment Problem is a type of mathematical optimization that helps match tasks or resources to agents in the best possible way, usually to minimize cost or time. In waste management, it's used to assign vehicles, routes, or waste sources to specific collection points, making operations smoother and more efficient. This model is especially good for short-term scheduling and balancing workloads within larger waste collection systems.

[8] Luo, Qin, and Gan (2024) introduced an assignment-based model for medical waste collection that balances workloads, showing how a similar approach could be used to optimize vehicle-task allocation in BOI zones.[9] The Surabaya case study on vehicle assignment demonstrated how assignment algorithms can optimize daily routes, which is directly relevant to BOI industrial waste collection scheduling.[9] These studies show that assignment models are great for improving resource efficiency and reducing downtime, especially in the operational phase after siting facilities with the single facility location model.

The assignment model is built for perfect pairings: every task gets exactly one worker, and every worker gets exactly one task. The number of tasks and workers always matches up, and each match comes with a specific, known cost. No one ends up with more than one assignment, and nothing is left undone. This model assumes you know all the costs and requirements ahead of time, and everything runs just as planned. In contrast, the FLP isn't about one-to-one matches. Instead, it's about finding the best spots for facilities and then deciding which demand points those facilities should serve there's no rule that says each demand point or facility has to be matched up exclusively.

### 4.2.3 Network Optimization / Routing

Network optimization models use graph theory to map out transportation systems, where nodes represent waste sources and facilities, and edges are the possible routes with their associated costs. The main goal is to cut down travel time or distance, all while making sure trucks don't exceed their capacity. These models are widely used for planning waste collection vehicle routes and creating efficient material flow networks.

[10] The 2023 SpringerLink review on waste collection routing describes a variety of network-based optimization methods that are useful for designing waste collection routes among BOI zones.[11] TUM's 2023 research on route optimization combines GIS and machine learning with network models, showing how new technologies can make routing more cost-effective.These methods are helpful for designing transport networks for BOI waste logistics by integrating route feasibility into the facility planning process.

Network flow models picture the system as a web of paths connecting different points. Every connection has its own limit for how much can pass through, and there's a cost for every unit that travels along it. The main idea is that whatever comes into a point unless it's a start or end point must go out as well, keeping everything in balance. The goal is often to send as much as possible from the start to the finish, or to do it as cheaply as possible. All available paths, capacities, and costs are mapped out clearly before planning begins. Unlike FLP, network flow models focus on how things move through a network rather than where to build new places to process or serve demand.

### 4.2.4 Facility Location Problems (Single Facility Location Model)

The Facility Location Problem (FLP) generally focuses on finding the best place to set up a facility so that the total cost usually a combination of transportation and setup costs is minimized. The Single Facility Location Model is the most basic and direct version of this, where the goal is to determine the optimal site for just one facility that can serve all demand points. This model is especially practical in cases where only one processing center is needed, and there are no strict capacity constraints. It helps planners identify a location that minimizes the overall distance or cost for everyone involved, making waste collection and processing more efficient for areas like the BOI zones. [12] Adeleke and Olukanni (2020) reviewed facility location strategies in waste management, supporting the use of single facility models for infrastructure planning when only one site is required.[13] Syam (1997) developed single facility approaches that are adaptable for identifying the best processing site in a given region, like the BOI zones.[14] Tarhan (2015) extended these concepts to dynamic environments, providing insights for adapting single facility models to changing waste flows in Sri Lanka.

The FLP is all about making smart choices on where to set up shop. You start with a list of possible locations and a list of customers or demand points. You get to decide which locations actually get built each has its own setup cost and then figure out which facility should serve each customer to keep transportation and overall costs as low as possible. In the simplest versions, facilities can handle any amount of demand; in more complex versions, each site has a limit. The costs, locations, and demand levels are all known and don't change unexpectedly. What sets FLP apart is that it's not about routing, one-to-one assignments, or detailed flows it's about choosing the best sites and assigning demand, often with the big-picture goal of keeping costs down for both building and transporting.

# 5 Methodology

This study adopts a systematic methodological framework encompassing four key components: Variable identification and Assumptions, Data collection, Model selection, Model development and Model testing / Validation. The methodology aims to construct a quantitative optimization model that identifies the most cost-effective location for a centralized waste processing facility serving selected BOI industrial zones in Sri Lanka.

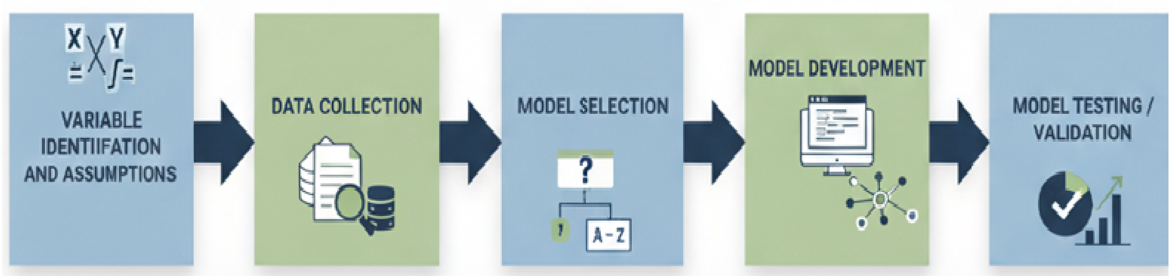



Figure 11: Slope of the Study

## 5.1 Variable Identification and Assumptions

### 5.1.1 Variables

The optimization model includes several variables representing the geographical, operational, and cost-related aspects of the system.

| Symbol | Description | Interpretation |
|---|---|---|
| **X** | Longitude of the waste management zone | Represents the longitudinal coordinate of the proposed centralized waste processing facility, which is the decision location to be optimized in the model. |
| **Y** | Latitude of the waste management zone | Represents the latitudinal coordinate of the proposed waste processing facility. Together with $X$, it defines the geographical position of the optimal site. |

| Symbol | Description | Interpretation |
| --- | --- | --- |
| $x_i$ | Longitude of BOI zone $i$ (for $i = 1, 2, \ldots, m$) | Indicates the longitudinal coordinate of the $i$-th BOI industrial zone considered in the study. |
| $y_i$ | Latitude of BOI zone $i$ (for $i = 1, 2, \ldots, m$) | Indicates the latitudinal coordinate of the $i$-th BOI industrial zone. |
| $Q_i$ | Waste quantity of the $i$-th BOI zone (t/year) | Represents the total annual amount of waste generated by the $i$-th BOI industrial zone, measured in tons per year. |
| **V** | Truck capacity (t) | Denotes the load capacity of a single transport vehicle, measured in tons. |
| **C** | Cost per kilometer | Represents the transportation cost incurred per kilometer per truck. |
| $n_i = \lceil \frac{Q_i}{V} \rceil$ | Number of trips required from zone $i$ | Represents the total number of truck trips needed to transport waste $Q_i$ from BOI zone $i$. |
| $t_i = \sqrt{(x_i - X)^2 + (y_i - Y)^2}$ | Distance between zone $i$ and facility | Represents the Euclidean distance between BOI zone $i$ and the facility. |
| $d_{\text{buffer}}$ | Buffer distance for sensitive zones | Defines the minimum allowable distance between the proposed facility and sensitive areas. |

### 5.1.2 Assumptions

- The study considers five main waste types plastic, paper, polythene, e-waste, and biodegradable waste aggregated as the total waste generated per BOI zone.
- A single centralized waste processing facility will be established to serve all selected BOI zones.
- The facility location is continuous; it can be anywhere within the feasible area.
- Each vehicle can transport all waste types together, up to its maximum capacity V.
- If the total waste generated by a BOI zone exceeds the truck's capacity, multiple trips will be made to complete the collection.
- The transportation cost per kilometer (C) is assumed to be constant across all trips.

- Distances between the Waste Management Zone and BOI zones are measured as straight-line (Euclidean) distances, acknowledging that actual travel paths may be slightly longer.
- The proposed facility is assumed to have sufficient capacity to process all collected waste.
- Environmental and regulatory constraints, such as exclusion zones (e.g., water bodies, residential areas) and buffer distances from sensitive locations (e.g., schools, hospitals), are strictly enforced.
- The system is static, representing a fixed planning period without dynamic changes.
- The vehicle type is uniform, meaning all trucks have identical capacity, performance, and cost characteristics.

## 5.2 Data collection

The data used in this study were obtained directly from the Lanka Responsible Care Council (LRCC). The dataset includes annual quantities (in tons per year) of five major waste types: plastic, paper, e-waste, biodegradable waste and fabric generated within the five selected BOI zones: Katunayaka, Biyagama, Seethawaka, Horana, and Koggala.

### 5.2.1 Katunayake

| Waste Type | Quantity (t/year) |
|---|---|
| Plastic | 2678 |
| Paper | 1056 |
| E-waste | 450 |
| Biodegradable waste | 2560 |
| Fabric | 1330 |

### 5.2.2 Biyagama

| Waste Type | Quantity (t/year) |
|---|---|
| Plastic | 1943 |
| Paper | 769 |
| E-waste | 389 |
| Biodegradable waste | 2867 |
| Fabric | 1098 |

### 5.2.3 Seethawaka

| Waste Type | Quantity (t/year) |
| --- | --- |
| Plastic | 1329 |
| Paper | 692 |
| E-waste | 360 |
| Biodegradable waste | 1309 |
| Fabric | 940 |

### 5.2.4 Horana

| Waste Type | Quantity (t/year) |
| --- | --- |
| Plastic | 237 |
| Paper | 348 |
| E-waste | 127 |
| Biodegradable waste | 568 |
| Fabric | 267 |

### 5.2.5 Koggala

| Waste Type | Quantity (t/year) |
| --- | --- |
| Plastic | 748 |
| Paper | 693 |
| E-waste | 257 |
| Biodegradable waste | 529 |
| Fabric | 749 |

## 5.3 Model Selection

#### Why the Single Facility Location Model is Selected

Among all the models reviewed, the Single Facility Location Model is the most relevant for this project. It is designed specifically to find the best site for one waste processing zone, making it a perfect fit when the project's scope only requires a single facility. This model simplifies the planning process, avoids unnecessary complexity, and still ensures cost-effective and accessible service for all demand points in the BOI area. Unlike transportation, assignment, or routing models, the single facility location model directly addresses the strategic challenge of selecting a site that minimizes costs and maximizes coverage for the entire zone. This model captures the core decision factors like setup cost and transport distances, which are crucial for BOI zones.It allows for straightforward optimization of facility siting and waste allocation, ensuring a balanced and efficient solution.The single facility location framework also sets the stage for future improvements or integration with other models if the system expands.


### Why the L-BFGS-B Algorithm is Selected

Limited-memory Broyden–Fletcher–Goldfarb–Shanno with Bounds is a numerical optimization algorithm in the quasi-Newton family, especially designed for large problems where variables are continuous and can be restricted by simple lower and upper bounds.

L-BFGS-B is Ideal for this optimization because:

- Variables are continuous: Optimal coordinates can be anywhere in a region, not just at fixed candidate sites.
- Objective is smooth: Transport cost is a differentiable function.
- Constraints are simple bounds: Facility must be inside Sri Lanka's bounding box, easily represented as lower/upper bounds for variables.
- Scales well: Even if the number of waste zones grows, or more geographic details are added, the method remains efficient and fast.
- Direct feasibility: It avoids solutions in forbidden zones or outside the country, because it checks boundaries automatically at each step.

## 5.4 Model Development

### 5.4.1 Objective Function

The objective is to minimize the total operational cost **Z**:

$$\text{Minimize } Z = C \times \sum_{i=1}^{m} n_i \times t_i$$

### 5.4.2 Constraints

The location $(X, Y)$ must satisfy the following geospatial constraints:

1. $(X, Y)$ is inside **Sri Lanka's border**

$$(X, Y) \in \text{Area}_{\text{Sri Lanka}}$$

2. $(X, Y)$ is **outside all exclusion zones** (e.g., water bodies, houses)

$$(X, Y) \notin \bigcup_{j=1}^{k} \text{ExclusionZone}_j$$

3. $(X, Y)$ is at least $\mathbf{d}_{\text{buffer}}$ away from all **sensitive zones**

$$\min_{l} \left(\text{Distance}((X, Y), \text{SensitiveZone}_l)\right) \geq d_{\text{buffer}}$$

## 5.5 Testing and Validation

### 5.5.1 Python Code

#### Loading Packages

Imports all necessary Python modules for geospatial analysis and optimization.

```
from google.colab import drive
drive.mount('/content/drive')
import warnings
warnings.filterwarnings('ignore')
import geopandas as gpd
import pandas as pd
from shapely.geometry import Point
```

```
from shapely.ops import unary_union
from scipy.optimize import minimize
import numpy as np
import matplotlib.pyplot as plt
```

#### Loading Geographic Data

Loads Sri Lanka's boundary and key exclusion zones from GIS files and prepares spatial layers.

```
world = gpd.read_file('ne_110m_admin_0_countries.shp')
sri_lanka = world[world['NAME'] == 'Sri Lanka']
sri_lanka_polygon = sri_lanka.geometry.unary_union


protected_areas_1 = gpd.read_file('WDPA_WDOECM_Aug2025.shp')
protected_areas_2 = gpd.read_file('Water_Bodies_and_Rivers.geojson')
buffer_zones = gpd.read_file('Sensitive_Sites_Schools_Hospitals.geojson')

crs = sri_lanka.crs
exclusion_layers = [protected_areas_1, protected_areas_2, buffer_zones]
for gdf in exclusion_layers:
    if gdf.crs != crs:
        gdf.to_crs(crs, inplace=True)


all_exclusion = gpd.GeoDataFrame(pd.concat(exclusion_layers, ignore_index=True),crs=crs)
all_exclusion_union = unary_union(all_exclusion.geometry)
exclusion_clipped = all_exclusion_union.intersection(sri_lanka_polygon)
sensitive_points = buffer_zones.copy()
buffer_distance = 0.0001
sensitive_coords = [(geom.x, geom.y) for geom in sensitive_points.geometry]
```

#### Loading BOI Zone Data

Defines BOI zone locations and waste quantities; sets vehicle and cost parameters for later calculations.

```
waste_zones_df = pd.DataFrame({
    'x': [79.89003, 80.01001, 80.72304, 80.13906,80.32473],
    'y': [7.17128, 6.96089, 6.96002, 6.73220, 5.98870],
    'Q': [8074, 7066, 4630, 1547, 2976]
```

```
})


vehicle_capacity = 5
cost_per_km = 20

waste_zones_df['Q'] /= 1000
vehicle_capacity /= 1000
cost_per_km /=1000
```

### Helper Functions

Implements spatial checks for candidate sites and defines the total cost calculation for optimization.

```
def inside_sri_lanka(x, y):
    point = Point(x, y)
    return sri_lanka_polygon.contains(point)

def outside_exclusion(x, y):
    point = Point(x, y)
    return not exclusion_clipped.contains(point)

def respect_buffer(x, y):
    for (xf, yf) in sensitive_coords:
        dist = np.sqrt((x - xf)**2 + (y - yf)**2)
        if dist < buffer_distance:
            return False
    return True

def is_feasible(xy):
    x, y = xy
    return inside_sri_lanka(x, y) and outside_exclusion(x, y) and respect_buffer(x, y)

def objective(xy):
    x, y = xy
    if not is_feasible(xy):
        return 1e9
    total_cost = 0
    for _, row in waste_zones_df.iterrows():
        xi, yi, Qi = row['x'], row['y'], row['Q']
        ni = np.ceil(Qi / vehicle_capacity)
```

```
        ti = np.sqrt((xi - x)**2 + (yi - y)**2)
        total_cost += cost_per_km * ni * ti
    return total_cost
```

### Optimization

Uses L-BFGS-B to find the cost-minimizing facility location within geographical and operational constraints.

```
centroid = sri_lanka_polygon.centroid
x0 = [centroid.x, centroid.y]



minx, miny, maxx, maxy = sri_lanka_polygon.bounds
bounds = [(minx, maxx), (miny, maxy)]

result = minimize(objective, x0, method='L-BFGS-B', bounds=bounds)

if result.success:
    opt_x, opt_y = result.x
    print(f"Optimal WMS location found at: ({opt_x}, {opt_y})")
    print(" ")
else:
    print("Optimization failed:", result.message)
```

### Visualization

Displays Sri Lanka, exclusion zones, BOI zones, and the optimal site on a map for validation and interpretation.

```
fig, ax = plt.subplots(figsize=(10,10))

sri_lanka.plot(ax=ax, color='none', edgecolor='black', linewidth=1)



exclusion_gdf = gpd.GeoDataFrame(geometry=[exclusion_clipped], crs=crs)
exclusion_gdf.plot(ax=ax, color='yellow', alpha=0.3, label='Exclusion Zones')



for (xf, yf) in sensitive_coords:
    circle = plt.Circle((xf, yf), buffer_distance, color='red', alpha=0.3)
    ax.add_patch(circle)
```

```
ax.scatter(waste_zones_df['x'],waste_zones_df['y'],s=30,color='black',label='BOI Zones')


ax.scatter([opt_x], [opt_y],color='red', marker='*',s=50,label='Optimal WMS Location')

ax.legend()
plt.title('Waste Management Facility Location with Geographic Constraints')
plt.xlabel('Longitude')
plt.ylabel('Latitude')
plt.show()
```

# 6 Results

## 6.1 Optimization Output

The optimization model produced a precise location for the centralized Waste Management Facility that minimizes total transportation costs. The identified coordinates, Longitude 80.0100 and Latitude 6.9609, represent the best possible site given the input waste zone data and all relevant geographic, exclusion, and buffer constraints. The output confirms that the selected location is inside the acceptable region, outside restricted zones, and maintains the required safety distances from sensitive sites.

## 6.2 Visualization

A spatial visualization generated from the model displays the Sri Lanka boundary, exclusion zones, BOI zone locations, and the computed optimal facility site. On the map, the facility's location is indicated by a red star, BOI zones by black dots, and exclusion areas in yellow. This figure allows stakeholders to visually verify that the proposed facility placement is strategic, feasible, and conforms to all imposed geographic restrictions.

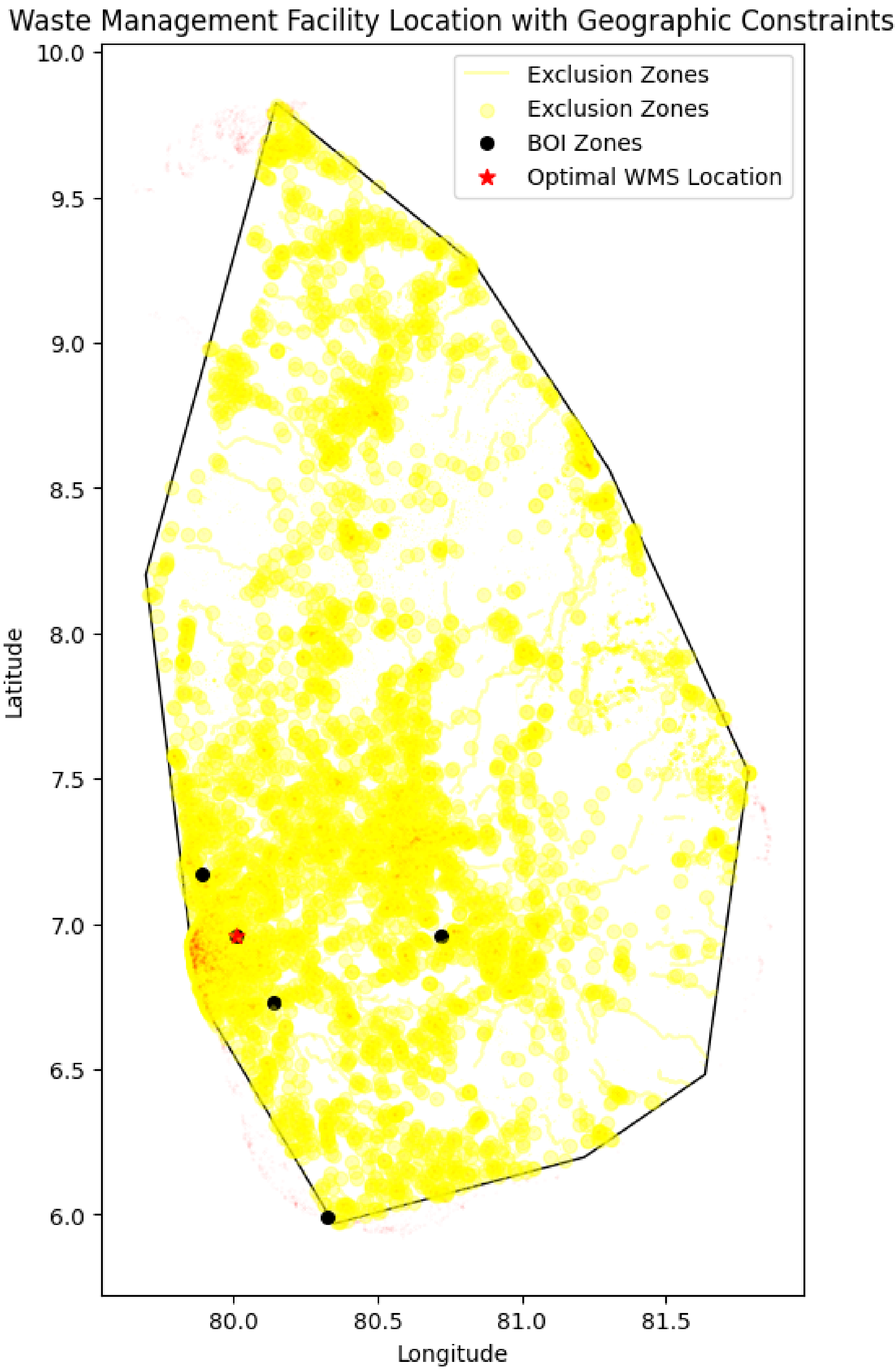



Figure 12: Optimal Location for waste management hub

## 6.3 Streamlit Application Demonstration

To enhance practical usability, the optimization tool was developed as an interactive Streamlit web application. Users can input zone details through a friendly interface, execute the optimization, and immediately view both the numerical results and an interactive solution map. The application streamlines the optimization process, making it easily accessible to planners and decision-makers without requiring advanced technical expertise.

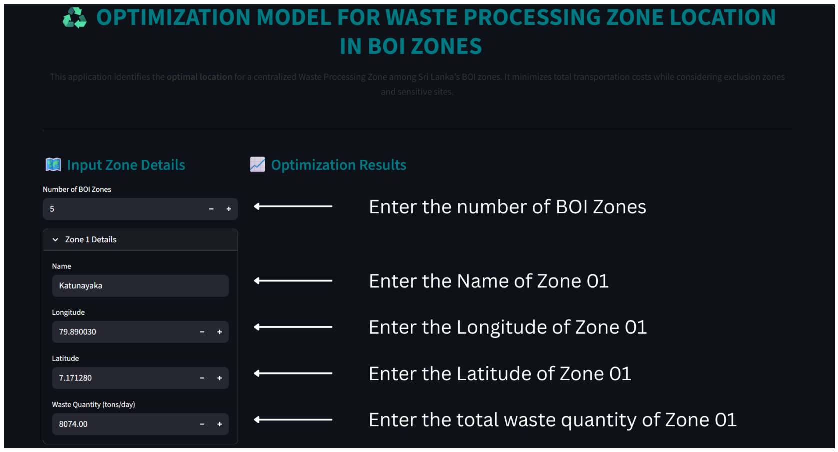



Figure 13: Input data to the application

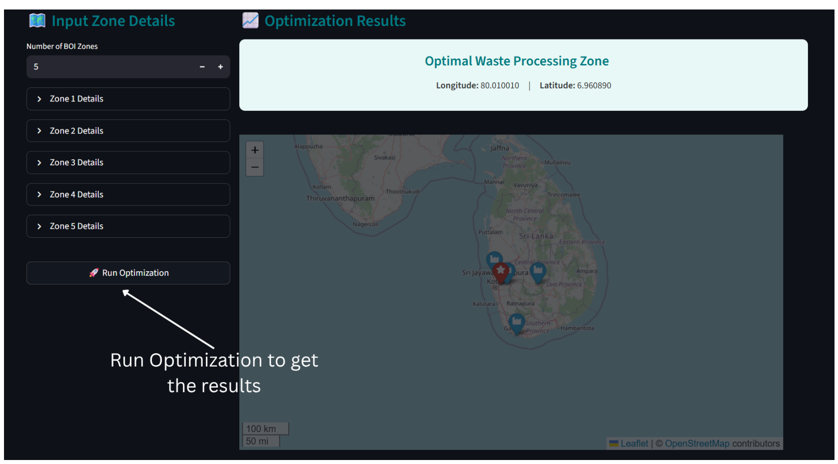



Figure 14: The Output of the application

# 7 Discussion

Discussion This project presents an integrated optimization framework for planning a centralized waste management system for the Board of Investment (BOI) industrial zones in Sri Lanka. It strategically combines multiple modeling categories Facility Location, Transportation (Routing), Assignment (Allocation), and Network Optimization under a unified decision-support approach. Each model plays a specific role in transforming raw spatial and operational data into actionable insights for efficient waste logistics. At the core of the project lies the Single Facility Location Model (SFLM), which identifies the most suitable site for a centralized waste processing facility. By adopting a Euclidean distance-based cost minimization approach, the model ensures computational simplicity and data reliability while addressing the lack of consistent road-network information across all candidate sites. This method provides a practical yet analytically robust framework for spatial decision-making, forming the foundation for subsequent operational models. Building upon this strategic layer, the Assignment (Allocation) model functions as a tactical mechanism for optimizing daily waste transport operations. Grounded in the Vehicle Assignment Problem (VAP) and supported by literature on workload balancing and multi-criteria decision-making, the model allocates vehicles and routes efficiently among BOI zones. This minimizes idle time and ensures the equitable distribution of collection responsibilities, directly enhancing the operational performance of the proposed SFLM-based network. The Transportation (Routing) model, formulated using Linear Programming (LP) and Geographic Information Systems (GIS) principles, provides the mathematical backbone for minimizing transportation distance and cost. By aligning with established Sri Lankan studies that successfully applied LP to optimize logistics networks, the project ensures methodological consistency and contextual relevance. The integration of GIS further enhances spatial accuracy, facilitating realistic route modeling and cost estimation across diverse industrial zones. At a more advanced analytical level, the Network Optimization model conceptualizes the waste transport system as a graph-theoretic network, emphasizing geospatial efficiency. This model determines optimal flow paths between sources and the facility, minimizing total travel distance and system-wide inefficiency. Drawing from recent innovations in Vehicle Routing Problems (VRP), Arc Routing, and GIS/Machine Learning (ML) integration, the project situates itself within contemporary global research on adaptive, data-driven logistics. The planned inclusion of IoT and GPS-based real-time monitoring in future phases reinforces the project's forward-looking stance, allowing dynamic optimization that responds to real-world variability in vehicle movement and waste generation. From a strategic research perspective, the Future Development phase positions the project within the emerging frontier of Multi-Objective Optimization (MOP). While the current stage focuses on single-objective cost minimization, the proposed evolution into a Multi-Facility, Multi-Objective framework will enable simultaneous consideration of economic, environmental, and operational factors. By incorporating objectives such as minimizing pollution, maximizing recycling efficiency, and reducing carbon emissions, this phase aligns with the global shift toward sustainable and circular economy-based logistics models. The transition from a single-facility LP model to a multi-objective system thus reflects both academic progression and practical scalability. Overall, the project demonstrates a coherent methodological flow from strategic facility location to operational allocation and network-level optimization anchored in established theory yet responsive to local constraints. It bridges analytical rigor with implementation feasibility, serving both as an academic contribution to logistics optimization literature and a practical blueprint for sustainable waste management planning in Sri Lanka's industrial context.

# 8 Conclution and Recomendation

## 8.1 Conclusion

This project successfully identified the optimal site for a centralized industrial waste processing center in Sri Lanka using Operations Research principles. The Single Facility Location Model provided a clear mathematical framework to minimize transportation and operational costs while maximizing accessibility across multiple BOI zones. The model was implemented and optimized using Python with the L-BFGS-B algorithm, ensuring accurate, efficient handling of spatial and operational constraints. Supported by real data from the Lanka Responsible Care Council and collaboration with major industry stakeholders, the results demonstrate that a single, strategically located facility can significantly improve recycling efficiency, reduce costs, and promote sustainable industrial waste management. Overall, this study shows how data-driven optimization and OR modeling can be used to solve real environmental challenges. The developed model can also serve as a foundation for future extensions such as multi-facility planning or integration with dynamic waste transportation models to further enhance sustainability across Sri Lanka's industrial zones.

## 8.2 Recommendations and Future Work

The findings of this study highlight a clear pathway toward establishing a centralized waste processing center for industrial zones in Sri Lanka. However, to strengthen and expand the impact of this work, the following recommendations and future developments are proposed:

1. Implementation and Policy Integration Authorities such as the Board of Investment (BOI) and Central Environmental Authority (CEA) should consider using the proposed model as a decision-support tool for planning and policy formulation. Embedding this model in waste management strategies can help identify cost-efficient and environmentally sustainable locations for future facilities.

2. Data Enhancement and Real-Time Monitoring Future research should incorporate dynamic and real-time data, including vehicle movement, traffic patterns, and seasonal variations in waste generation. Integrating GPS and IoT-based data collection systems can further refine the model's accuracy and operational relevance.

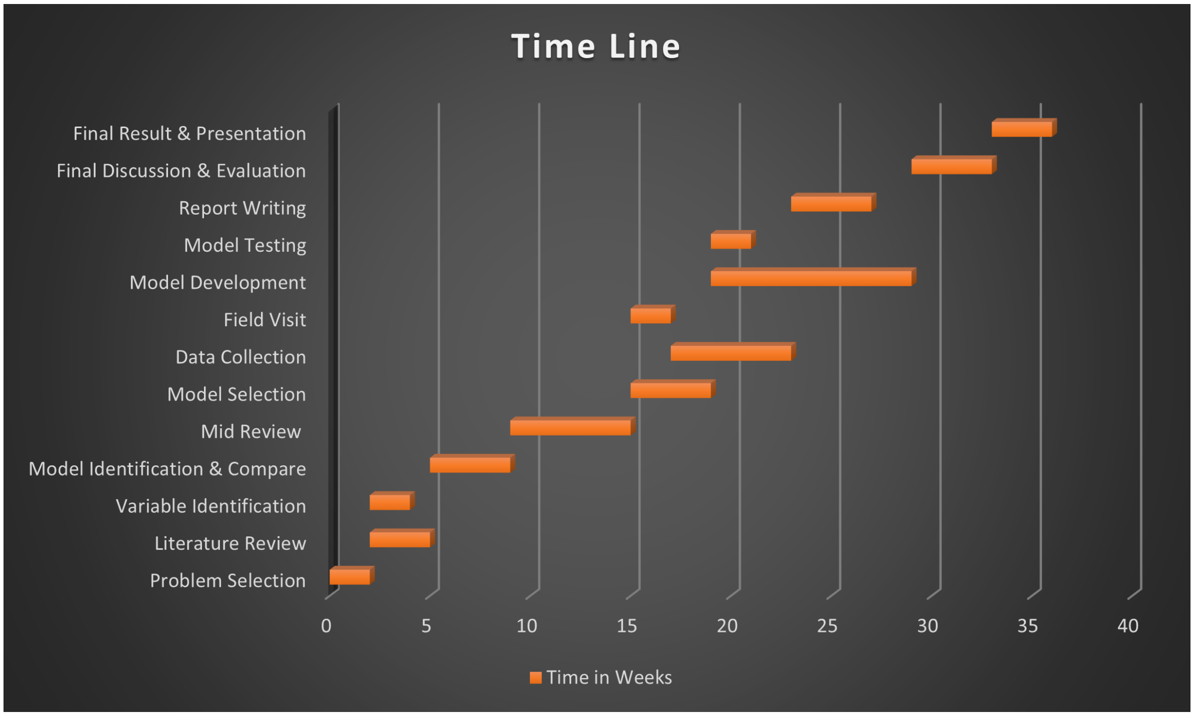
3. Expansion to Multi-Facility Models While this study focused on a single centralized facility, future studies could explore multi-facility location models to evaluate the potential benefits of having multiple regional waste centers. This would allow for better waste distribution and reduced transportation distances for larger industrial networks.

4. Environmental and Social Impact Assessment Adding environmental risk analysis, social acceptability, and life-cycle assessment (LCA) into future optimization frameworks will

ensure that sustainability is evaluated not only economically but also ecologically and socially.

5. Model Integration and Automation Future versions of this model can be automated into a GIS-based decision support system (DSS), allowing policymakers and industry leaders to visualize, test, and update waste management strategies interactively using real-world data and constraints.

# 9 Timeline


Time Line
Final Result & Presentation
Final Discussion & Evaluation
Report Writing
Model Testing
Model Development
Field Visit
Data Collection
Model Selection
Mid Review
Model Identification & Compare
Variable Identification
Literature Review
Problem Selection
0
5
10
15
20
25
30
35
40
Time in Weeks

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# 11 Appendix

Appendix A: Lanka Responsible Care Council Official Letter of Problem Confirmation

Responsible Care®
OUR COMMITMENT TO SUSTAINABILITY

**LANKA RESPONSIBLE CARE COUNCIL**

*The Chemical Industry's Initiative to Protect the Environment and to Promote Health and Safety*



4th May 2025

**To Whom It May Concern,**

We are pleased to acknowledge and support the request made by the following group of third-year undergraduate students from the Faculty of Science, University of Peradeniya, reading for a degree in Statistics and Operations Research:

S20801 – K.A. Sachethana Abeyrathne

S20810 – S.P. Gayathri Bandara

S20821 – E.U.M.A.N. Ekanayake

S20825 – K.G. Chanya Gamage

S20826 – R.G.J. Nilanka Gamage

S20830 – K.P. Sakuna Himal

S20841 – T.T. Asini S. Karunarathna

S20863 – P.V. Kavindu Sachintha

The Lanka Responsible Care Council, the national representative body of the global Responsible Care Programme in Sri Lanka, established under the supervision and guidance of the International Council of Chemical Associations (ICCA) and the American Chemistry Council (ACC), USA, is happy to offer its fullest support for their academic project.

The students will be conducting research on the topic:
**"Optimization of the Recycling Collection Network for BOI Industrial Zones in Sri Lanka."**

We recognize the value of this research in promoting efficient and sustainable waste management practices and are committed to providing the necessary data and guidance to facilitate their study.

We wish the team all the best in their project and look forward to a fruitful collaboration.

Thank you
Your Faithfully

Lakmini Edirisnghe, Ph.D.
Secretary
Lanka Responsible Care Council, Sri Lanka

https://www.lankaresponsiblecare.lk

Appendix B: Lanka Responsible Care Council Official Collaboration and Guidance Letter

Responsible Care®
OUR COMMITMENT TO SUSTAINABILITY

**LANKA RESPONSIBLE CARE COUNCIL**

*The Chemical Industry's Initiative to Protect the Environment and to Promote Health and Safety*



5th May 2025

Dear Research Team,

**Subject: Guidance on Research Focus Areas and Waste Types**

Based on the discussion we had with the Board of Investment (BOI) Sri Lanka, the zones identified as the highest waste-generating areas are as follows:

- Katunayake Export Processing Zone
- Biyagama Export Processing Zone
- Seethawaka Export Processing Zone
- Horana Export Processing Zone
- Koggala Export Processing Zone

You are encouraged to prioritize these zones in your initial research activities.

Regarding waste types, while various categories of waste are generated across the zones in differing quantities, the most prominent recyclable waste types include paper, cardboard, plastic, e-waste, and fabric. These waste types are considered to have significant recyclable value and should therefore be given special attention in your assessment.

We will coordinate with the relevant BOI officers to facilitate access to waste generation data from these zones.

Thank you for your cooperation.

Your faithfully,

Lakmini Edirisinghe
Executive Secretary
Lanka Responsible Care Council

https://www.lankaresponsiblecare.lk