MethodsX 13 (2024) 102813

Contents lists available at ScienceDirect

MethodsX

journal homepage: www.elsevier.com/locate/methodsx

Optimizing material circularity pathways in industrial waste streams: A decision-making model ☆

L.G.L.M. Edirisinghe [a,b,*], A.A.P. de Alwis [a,b,c], S. Prakash [d], M. Wijayasundara [d]

[a] *University of Moratuwa, Moratuwa 10400, Sri Lanka*
[b] *Lanka Responsible Care Council, Sri Lanka*
[c] *National Innovation Agency, Sri Lanka*
[d] *Deakin University, Melbourne 3000, Australia*

ARTICLE INFO

Method name:
Optimization method for waste material circularity

Keywords:
Industrial waste management
Sustainable practices
Waste circularity pathways
Recovery technologies
Decision-making model

ABSTRACT

The increasing pressures of environmental regulation and the introduction of new policy frameworks by various nations have accelerated the popularization of industrial solid waste management and recovery, underscoring the transition towards a circular economy. This paradigm shift emphasizes the importance of material recovery, reuse, and recycling of industrial waste to minimize environmental impact and enhance sustainability. Despite the availability of individual approaches for waste recovery, there exists a significant gap in the systematic selection of optimal recovery pathways that facilitate the reintegration of materials into the production cycle. Addressing this gap, our study introduces a novel optimization model designed to identify the most efficient material circularity routes that leverage both the technical and biological cycles of the circular economy framework. Utilizing the Genetic Algorithm optimization tool in MATLAB, our model prioritizes pathways that maximize material recovery and profit generation simultaneously. This dual-objective function serves as the cornerstone of our analysis, ensuring a balanced approach to environmental sustainability and economic viability. The model's efficacy was tested on pre-calculated quantities of fabric waste generated by the Biyagama Export Processing Zone, providing a practical case study for its application. Our findings reveal diverse scenarios under which the model can allocate varying weights to each objective, demonstrating its flexibility and utility as a decision-making tool for stakeholders in the waste management sector. The results indicate that the model is not only capable of optimizing waste circularity pathways for maximum material recovery and profit generation but also offers a customizable framework that can adapt to the specific priorities of different stakeholders. This research contributes to the existing body of knowledge by filling a critical gap in the selection of sustainable waste recovery pathways, offering a practical, optimized, and scalable solution that can significantly advance the goals of the circular economy in the industrial sector.

- Decision-making model for stakeholders in the waste management sector.
- Model selects the best material recovery pathways.
- Textile industrial fabric waste stream used as a pilot to test the model's effectiveness.

☆ **Related research article:** Not applicable.

* Corresponding author at: University of Moratuwa, Moratuwa 10400, Sri Lanka.
E-mail addresses: 198063P@uom.lk (L.G.L.M. Edirisinghe), ajith@uom.lk (A.A.P. de Alwis).

https://doi.org/10.1016/j.mex.2024.102813
Received 25 April 2024; Accepted 20 June 2024
Available online 24 June 2024

Specifications table

Subject area:	*Environmental Science*
More specific subject area:	*Industrial waste circularity*
Name of your method:	*Optimization method for waste material circularity*
Name and reference of original method:	*Not applicable*
Resource availability:	*Not applicable*

Introduction

The growing industrial activities in developing nations have triggered a surge in industrial solid waste generation [10], presenting a multifaceted challenge to environmental sustainability and public health [12]. Conventional waste management practices, predominantly landfilling, have proven inadequate in addressing the escalating volume of industrial waste [2]. Landfills occupy vast land areas and contribute to soil, air, and water pollution through the generation of leachate and the emission of greenhouse gases, primarily methane, with industrial waste residues contaminating soil and water due to improper disposal practices [11]. Moreover, the improper disposal and decay of solid waste further exacerbate climate change [3]. This scenario underscores the urgent need for a comprehensive solution to manage industrial waste more effectively, mitigating its detrimental impact on the environment and human well-being [6].

In response to the shortcomings of traditional waste management approaches, the current trend in waste management is shifting towards sustainability-driven practices, notably the circular economy framework [5]. The circular economy paradigm emphasizes the importance of minimizing waste generation and maximizing material reuse and recycling throughout the product life cycle [4]. Initiatives promoting circular economy principles aim to transform waste into valuable resources by adopting innovative business models that prioritize delivering solutions and services over conventional product-centric approaches [1]. Additionally, there's a growing recognition of the environmental benefits of eco-design and integrating waste circularity into the material supply chain [8]. This holistic approach reflects a broader societal shift towards sustainability and resource efficiency, marking a departure from the linear "take-make-dispose" model of production and consumption [7]. The selection of the most suitable waste circularity pathway significantly impacts both economic and environmental performance [9]. Therefore, establishing an effective decision-making process is crucial for identifying appropriate waste circularity pathways and devising strategies to minimize waste generation while maximizing its reintegration into the material supply chain. This optimization of waste circularity pathways is essential to enhance economic returns and maximize material recovery from waste.

To address the complexity of industrial waste management, this paper proposes a comprehensive decision-making model tailored specifically for industrial waste. Unlike previous models that often focus on specific industries or waste streams, this proposed model aims to provide a general framework applicable across diverse industrial sectors. By integrating multi-objective optimization and multi-criteria decision-making methods, this model seeks to maximize economic returns and material recovery while minimizing environmental impact. Through systematic analysis and prioritization of various factors, such as economic viability, environmental sustainability, and regulatory compliance, stakeholders can make informed decisions to enhance the efficiency and effectiveness of industrial waste management practices.

In light of the existing gap in generalized decision-making models for industrial waste circularity, this study presents a novel and inclusive approach to address this challenge. By introducing a comprehensive decision-making model capable of accommodating the complexities of diverse waste streams and industries, this research aims to provide stakeholders with a versatile tool for strategic waste management. Ultimately, the objective is to contribute to sustainable practices in the industrial sector while promoting environmental stewardship and economic prosperity. Through the integration of advanced optimization and decision-making techniques, this model endeavors to optimize the balance between economic objectives and environmental sustainability, thereby facilitating the transition towards a more circular and resource-efficient industrial ecosystem.

Method details

Nomenclature

Vi	capacity of recovery technology
fi	efficiency of recovery technology
Ri	total revenue generated from all recovery technologies
Ci	total cost involved for manufacturing of products from all recovery technologies
R_i	revenue generated per unit weight, product generated from (i) recovery technology

The Fig. 1 illustrate the proposed structure of the optimization model. In developing a generalized decision-making model, consideration is given to the processing of all waste types through various recovery methods. For instance, waste type 1 is assumed to be recoverable through all available recovery processes. However, in real-world scenarios, this assumption may not hold true, as certain waste streams may be incompatible with specific recovery processes.

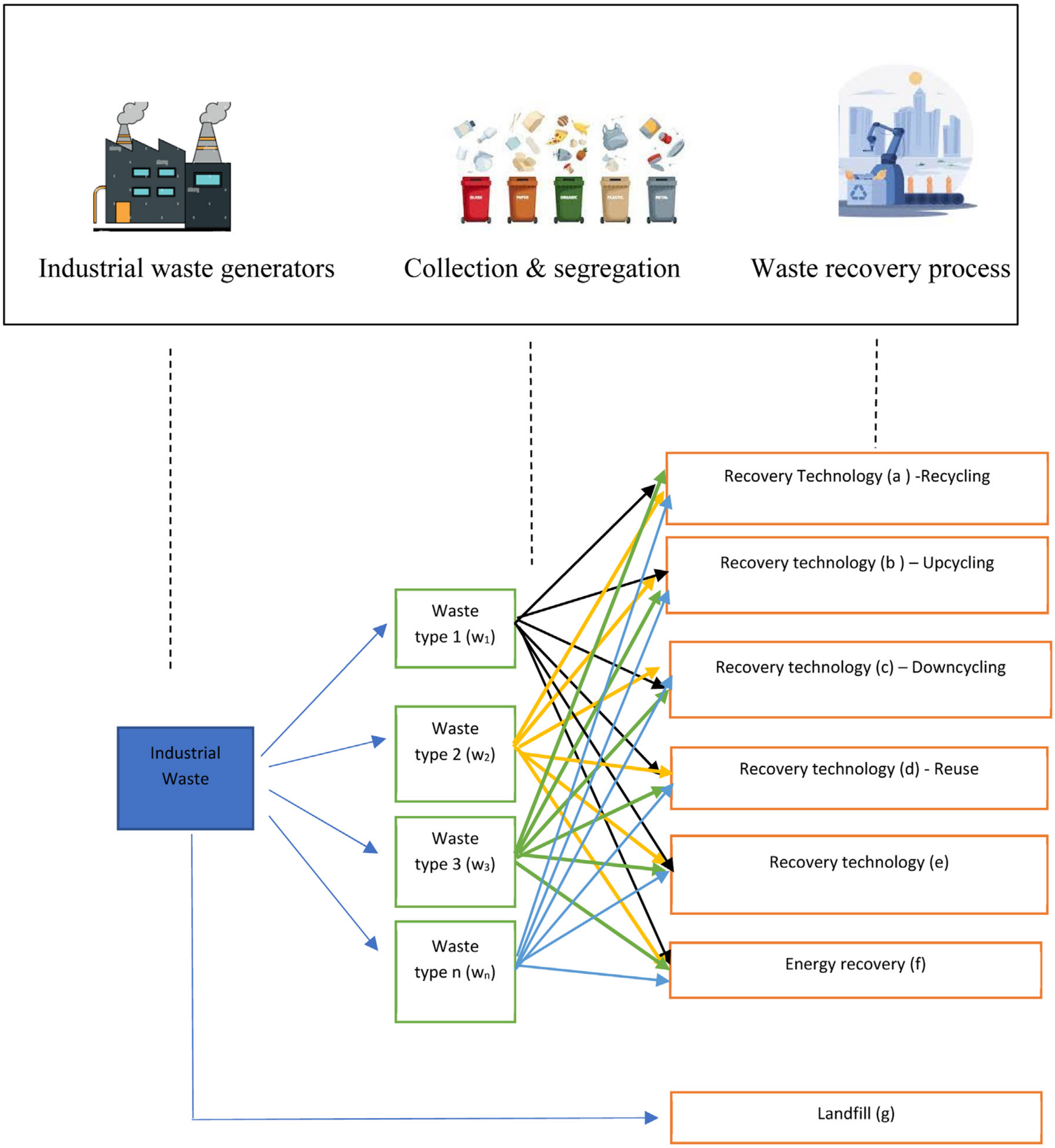

Fig. 1. Structure of the proposed optimization model.

Optimization of the model

In the presented decision-making model, the optimization process entails addressing two primary objectives considering whole recovery processes:

Objective 1: Maximizing annual material recovery
Objective 2: Maximizing annual profit

To concurrently optimize both material recovery and profit within this model, the genetic algorithm (GA) optimization tool is employed. The GA simulates the natural evolution process, utilizing selection, crossover, and mutation operations to iteratively enhance solutions. Due to its well-documented efficacy in addressing similar objectives, the genetic algorithm tool was selected for optimizing the model. This approach facilitates the simultaneous consideration of both objectives, striving for an optimal solution. The optimization problem was effectively solved using MATLAB Simulink, incorporating the GA optimization tool.

Define the objectives

- Objective 1: Maximizing material recovery from recovery technologies: This objective seeks to maximize the efficient recovery of waste through various recovery technologies.
- Objective 2: Maximizing profit: This objective centers on optimizing the profit derived from the recovered materials, taking into account factors such as market pricing and production costs.

Objective function formulation

The objective function combines the two objectives in a way that captures their respective importance, typically accomplished through the use of weighted sums or other aggregation techniques. For example:

Objective function f (x) = Q_1{-1} Objective 1 + Q_2 {-1} Objective 2

In this equation, Q1 and Q2 serve as weight factors determining the relative significance assigned to each objective. The adjustment of these weights can be based on the specific priorities and preferences of stakeholders or decision-makers involved in the waste circularity model.

Decision variables

The decision variables constitute the adjustable parameters that direct the optimization of the objectives. In the context of this waste decision-making model, the material allocation for each recovery pathways are decision variables. here there are the recovery pathways;

$w_1 x_i$	quantity of waste type 1 send to recovery route (i)
$w_2 x_i$	quantity of waste type 2 send to recovery route (i)
$w_3 x_i$	quantity of waste type 3 send to recovery route (i)
$w_n x_i$	quantity of waste type n send to recovery route (i)

where, i = a,b,c,d,e,f

Constraints

Constraints represent the conditions or limitations that must be satisfied throughout the optimization process. In the development of this model, the following constraints have been identified:

- Recovery process or technology capacity
- Efficiency of the technology
- Waste types
- Feasibility of processing at identified recovery process

Objective (1) Maximize M,

M_{max}- Maximum material recovery from waste:

$$M_{max} = \sum \sum \left(w_j x_i f_i\right) \tag{1}$$

Where i = a, b, c, d, e, f

$$j = 1, 2, 3, \ldots\ldots n$$

Accounting for energy recovery as equivalent weight

In this proposed model, we have considered energy recovery as one aspect of material circularity. However, it is important to note that if we recover energy from a material, the material itself is consumed and thus not available for further recovery. Therefore, material recovery is not possible through energy recovery processes; the material recovery rate in such cases is zero, as the material is converted into energy.

To address this limitation in our model, we used the quantity of original fuel saved through energy recovery as a proxy for the recovered material amount. This approach assumes that if energy were not recovered from the material, an equivalent amount of original fuel would be required to fulfill the energy demand. By doing so, we can integrate the benefits of energy recovery into our model while acknowledging the fundamental distinction between material and energy recovery processes.

Thus, our model calculates the maximum material recovery objective function by incorporating the original fuel saving quantity as an equivalent measure of material recovery. This allows us to maintain a comprehensive perspective on resource efficiency and sustainability, even though direct material recovery from energy recovery processes is not feasible. Therefore, the calculation of original fuel weight savings can be expressed using the following equation:

$$\text{Total fuel weight saving} = w_j x_f f_f C_0 \tag{2}$$

Table 1
Fabric waste composition.

Type of fabric waste	Composition
Cotton	$W_1 = 0.21$
Polyester	$W_2 = 0.26$
Nylon	$W_3 = 0.31$
Mixed	$W_4 = 0.22$

Where,
w_j x_f - total material sends to the recovery routes f
f_f - efficiency factor of recovery route f

$$C0 = \frac{\text{Calorific value of the waste}}{\text{calorific value of the next best fuel}} \tag{3}$$

Incorporating the C_0 value to the Eq. (1) the following Eq. (4) has been derived

$$M_{max} = \sum\sum w_j x_i f_i + + \sum(w_j x_f f_f C_0 \tag{4}$$

Where,
j = 1,2,4…n

$$i = a, b, c, d, e$$

Objective function (2) Maximize profit:
E- total annual profit through material circularity
R- total annual revenue generated from all recovery routes
C- Total annual cost involved for manufacturing of products from all recovery routes

$$E = \sum_{i=a}^{f} Ri - Ci \tag{5}$$

The equation can be extended to accommodate any number of waste streams and recovery technologies

Method validation

To apply the model to real-world data, we have chosen to focus on fabric waste generation within the Biyagama Export Processing Zone (BEPZ). According to our analysis conducted within BEPZ, it has been observed that the zone generates approximately 13 MT of fabric waste each month. Furthermore, the composition of this fabric waste during the reference period in 2022 is detailed in Table 1.

The Fig. 2 further outlines the framework of the proposed decision-making model, which focuses on four selected fabric types and their circulation through seven recovery technologies. Specifically, cotton waste can be channeled through recovery technologies a, c, d, f, and g, while polyester waste can circulate through routes b, c, e, f, nylon waste can be directed through routes b, c, e, f and mixed waste can be forwarded through routes e and f.

To identify the most optimal recovery routes, the model will undergo optimization with the integration of two objective functions, as described in section 2.1

Materials generated from industries are transferred to a material collection and recovery center for further processing. In this center, materials are prepared and sent to various recovery technologies. In this case study, all incoming materials to the center were transferred to the appropriate recovery technologies

The collection and pre-processing cost encompass various elements such as procurement of waste material, collection, transportation, and the expenses incurred during activities at the collection and separation center. These costs are calculated based on prevailing prices as of March 2023.

These cost elements are then combined and detailed in Table 2, representing the total cost incurred in manufacturing 1 MT of product developed from the recovery technology. The foundational calculations were initially conducted as independent assessments and fed into the model as input parameters. It's worth noting that these factors are subject to variation according to the market price of good and services over time; however, the model is adaptable and capable of accommodating changes related to these input parameters.

The following factors were considered when developing the model

- *Only the efficiency factor of the recovery route will affect the material recovery process.*
- *Maximum material processing in a plant ≤ Maximum monthly capacity of the plant*
- *All recovery plant gives their first priority for BEPZ waste.*
- *Efficiency factors based on the currently available technologies.*

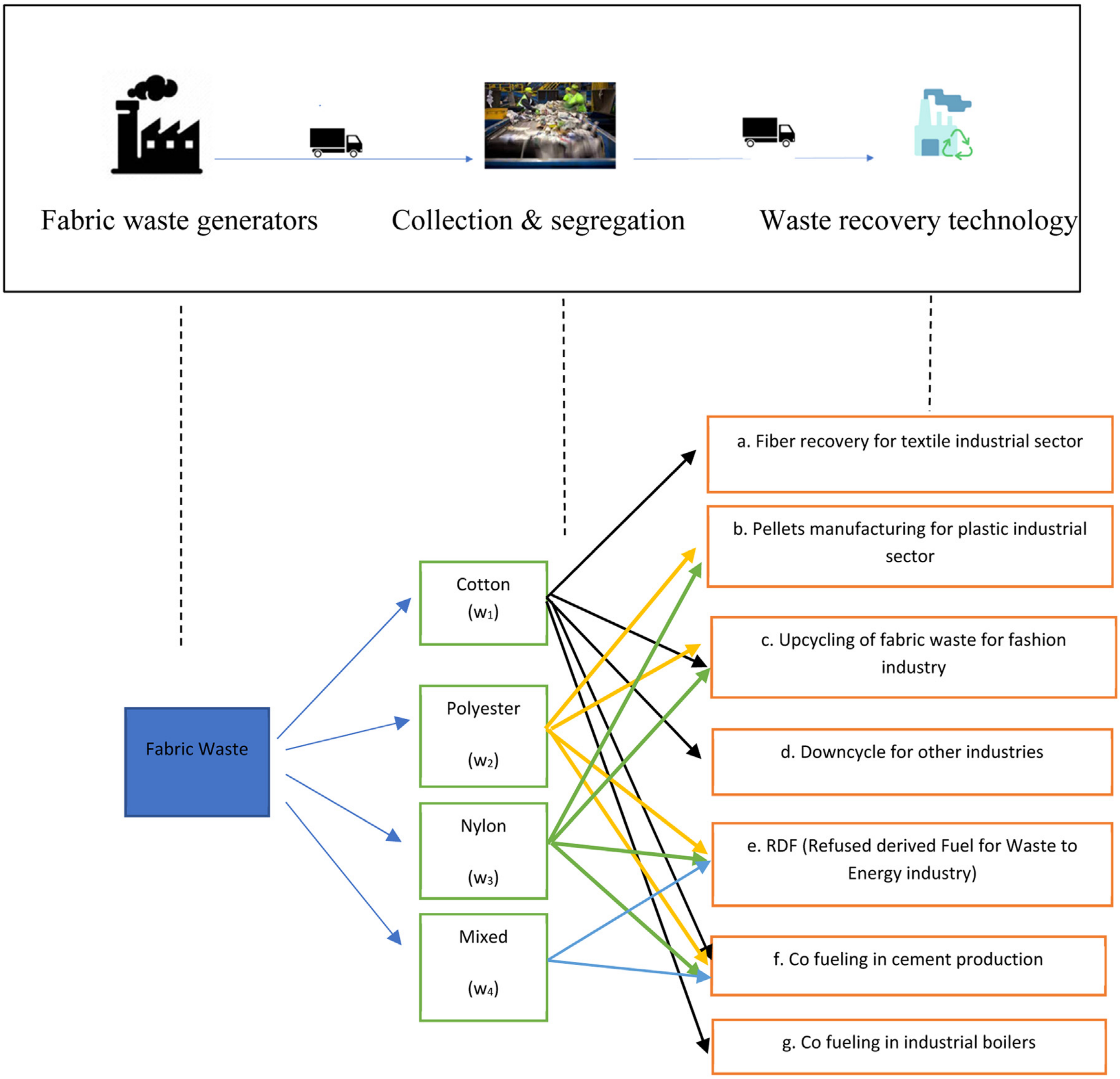

Fig. 2. Structure of the optimization model for fabric waste.

Table 2
Input parameters.

Waste recovery path proposed	Max. Efficiency of the technology	Maximum Capacity of the plant (MT/month)	Total cost for production of unit weight (USD)	Selling price of product (1MT) (USD)
Fiber recovery for textile industrial sector (cotton)	92 %	Unlimited*	750	1600
Pellets manufacturing for plastic industrial sector (Polyester)	95 %	300	60	874
Pellets manufacturing for plastic industrial sector (nylon)	95 %	300	85	900
Upcycling of fabric waste for fashion industry	50 %	5	70	1400
Downcycle for other industries (wiping cloths, carpet padding, and sound insulation)	95 %	1	24	170
RDF (Refused derived Fuel for Waste to Energy industry)	85 %	15,000	51.3	114.3
Co- fueling in cement production	90 %	3500	69	88.5
Co -fueling in industrial boilers	95 %	80	57	190

Table 3
Assigning of weightage factor for each objective.

Scenario	Weightage for Economic value addition	Weightage for Material Recovery
Scenario 1	25 %	75 %
Scenario 2	50 %	50 %
Scenario 3	75 %	25 %

- *Transportation costs and other local expenses are determined based on the market prices in March 2023*
- *USD to LKR conversion rate 360*
- *Currently, there is no limit on exporting for recycling*

Decision variables in the case study:

w_1x_a	quantity of cotton waste send to recovery route (a)
w_1x_c	quantity of cotton waste send to recovery route (c)
w_1x_d	quantity of cotton waste send to recovery route (d)
w_1x_f	quantity of cotton waste send to recovery route (f)
w_1x_g	quantity of cotton waste send to recovery route (g)
w_2x_b	quantity of polyester waste send to recovery route (b)
w_2x_c	quantity of polyester waste send to recovery route (c)
w_2x_e	quantity of polyester waste send to recovery route (e)
w_2x_f	quantity of polyester waste send to recovery route (f)
w_3x_b	quantity of nylon waste send to recovery route (b)
w_3x_c	quantity of nylon waste send to recovery route (c)
w_3x_e	quantity of nylon waste send to recovery route (e)
w_3x_f	quantity of nylon waste send to recovery route (f)
w_4x_c	quantity of mixed waste send to recovery route (e)
w_4x_c	quantity of mixed waste send to recovery route (f)

Objective (1) Maximize M,
M_{max}- maximum material recovery from fabric waste

$$M_{max} = \sum \left(w_1x_af_a + w_1x_cf_c + w_1x_df_d + w_1x_ff_fC_0 + w_1x_gf_gC_0\right) + \sum \left(w_2x_bf_b + w_2x_cf_c + w_2x_ef_eC_0 + w_2x_ff_fC_0\right) + \sum \left(w_3x_bf_b + w_3x_cf_c + w_3x_ef_eC_0 + w_3x_ff_fC_0\right) + \sum \left(w_4x_ef_eC_0 + w_4x_ff_fC_0\right) \tag{6}$$

Objective function (2) Maximize profit:
E- total profit through material circularity
Ri- total revenue generated from all recovery routes
Ci- Total cost involved for manufacturing of products from all recovery routes

$$E = \sum_{i=a}^{g} Ri - Ci \tag{7}$$

$$E_{max} = \sum [\left(f_a\left(w_1x_a\right)S_a - C_a\right) + \left(f_b\left(w_2x_b + w_3x_b\right)S_b - C_b\right) + \left(f_c\left(w_1x_c + w_2x_c + w_3x_c\right)S_c - C_c\right) + \left(f_d\left(w_1x_d\right)S_d - C_d\right) + \left(f_eC_0\left(w_2x_e + w_3x_e + w_4x_e\right)S_e - C_e\right) + \left(f_f\ C_0\left(w_1x_f + w_2x_f + w_3x_f + w_4x_f\right)S_f - C_f\right) + \left(f_gC_0\left(w_1x_g\right)S_g - C_g\right)] \tag{8}$$

However, this equation can be extended to accommodate any number of recovery technologies and any number of recovery plants. For example, in the context of nylon material recycling in Sri Lanka, there may be several units in the country. However, the equation has been limited in this model to encompass only seven recovery routes, even though there might be more recovery routes available for fabric waste. This simplification was made to reduce the complexity of the model, but the equation can be generalized to accommodate any number of recovery technologies and any number of plants within each recovery route.

The primary focus lies in optimizing both the maximum annual material recovery and the maximum annual profit derived from fabric waste through various recovery technologies. In this optimization process, specific case scenarios, as depicted in Table 3, have been chosen to derive the optimal values. We adjust the weight factor for each objective to observe variations in the optimization values.

Base case scenario

In this scenario, material allocation was evenly distributed among waste recovery pathways. For instance, concerning cotton waste – it can recoverable through five distinct pathways. Therefore, an equal distribution of 20 % of the material per recovery pathway was assigned.

In the base scenario, the distribution of waste among recovery pathways are uniform. However, each recovery plant operates within defined capacity constraints, limiting the volume it can process within a set timeframe. According to the base case scenario, certain plants receive an excessive amount of waste beyond their processing capabilities. This surplus, due to the inability to be

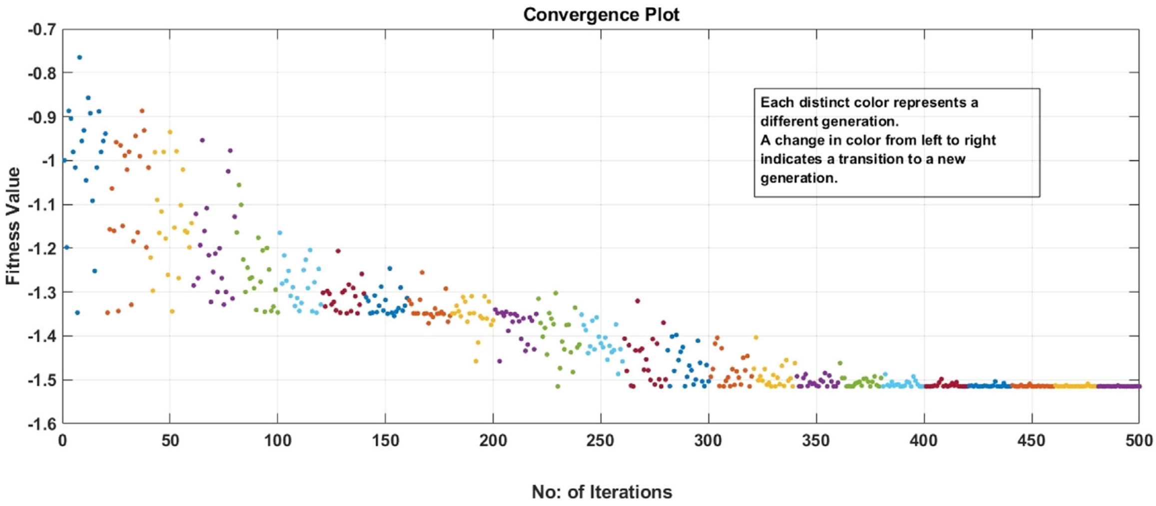

Fig. 3. Fitness value function.

Table 4
Input material allocation for each recovery pathway in the base case & optimized scenarios 1,2,3.

Recovery pathway	Base case (%)	Scenario 1	Scenario 2	Scenario 3
Cotton waste				
Cotton diverted to cotton recycling plant	0.2	0.4000	0.5194	0.3576
Cotton diverted to upcycling	0.2	0.1500	0.1114	0.1134
Cotton diverted to co-fuel cement	0.2	0.1500	0.1114	0.1148
Cotton diverted to downcycling	0.2	0.1501	0.1122	0.2492
Cotton diverted to industrial boilers	0.2	0.1499	0.1456	0.1650
Nylon waste				
Nylon diverted to nylon recycling plant	0.25	0.7002	0.7000	0.6205
Nylon diverted to upcycling	0.25	0.1000	0.1000	0.1289
Nylon diverted to co-fuel cement	0.25	0.1000	0.1000	0.1255
Nylon diverted to RDF	0.25	0.1000	0.1000	0.1251
Polyester				
Polyester diverted to Polyester recycling plant	0.25	0.4851	0.2536	0.4213
Polyester diverted to upcycling	0.25	0.1716	0.2456	0.1149
Polyester diverted to co-fuel cement	0.25	0.1716	0.2551	0.1143
Polyester diverted to RDF	0.25	0.1716	0.2456	0.3496
Mixed waste				
Mixed waste diverted to RDF	0.50	0.5001	0.4997	0.7849
Mixed waste diverted to co-fuel cement	0.50	0.4999	0.5003	0.2151

accommodated within the plant's capacity, is transferred to the node call *landfill out* within the model as it cannot be effectively processed. In this base scenario, 2524 MT of waste have been directed to the landfill out as unprocessed material. When resources are evenly distributed among pathways and certain pathways receive less allocation, they may only process the amount they've been granted. This creates a scenario where optimization becomes imperative to maximize material recovery while maximize profit. Scientifically, this calls for a strategic reallocation of resources based on the potential yield of each pathway, ensuring an efficient utilization of resources to achieve the best possible outcome in material recovery and profit generation. In the base case scenario, without optimization, the uneven allocation might lead to suboptimal utilization of resources, hindering the overall potential for both material recovery and profit.

Therefore, in order to optimize the total annual material recovery and annual profit, aimed to optimize the objective functions. We initialized the model with base case values and utilized the GA optimization tool to refine the function. Eventually, it converged, achieving a fitness value (t) of -1.5, as shown in Fig. 3. According to the figure each distinct color represents a different generation. A change in color from left to right indicates a transition to a new generation.

It shows that the algorithm has reached a point where the fitness values of the population are stabilizing or no longer significantly changing over successive iterations or generations. For instance, in the context of a genetic algorithm, when discussing the convergence of the fitness value function, it implies that the algorithm has reached a stage where the population's fitness values are no longer changing significantly over subsequent generations, suggesting a potential optimal or near-optimal solution has been found.

Then, analyzed the optimum value of annual material recovery and annual profit for different scenarios.

Table 5
Material recovery and profit for base case, scenario 1,2, & 3.

Recovery technology	Base case		Scenario1		Scenario 2		Scenario 3	
	Material recovery Base case (MT)	Total profit base case (USD in Thousands)	Material recovery Scenario 1 (MT)	Total profit Scenario 1 (USD in Thousands)	Material recovery Scenario2 (MT)	Total profit Scenario 2 (USD in Thousands)	Material recovery Scenario 3 (MT)	Total profit Scenario 3 (USD in Thousands)
Fiber recovery for textile industrial sector	502.66	427.26	1005.23	763.88	1305.46	1109.64	898.69	854.45
Pellets manufacturing for plastic industrial sector	957.78	780.59	2682.71	1935.12	2679.95	2181.48	2377.29	2186.41
Pellets manufacturing for plastic industrial sector	803.30	653.88	1558.62	1103.20	814.30	663.65	1353.62	1268.72
Upcycling of fabric waste for fashion industry	90.00	119.70	90.00	119.70	90.00	119.70	90.00	119.70
Refused derived Fuel for Waste to Energy industry (RDF)	3098.00	70.46	296.40	43.27	291.00	45.55	296.39	43.27
Co - fueling in cement production	3613.33	45.89	2279.00	233.70	2512.00	158.26	3709.55	150.62
Co - fueling in industrial boilers	345.00	43.27	2665.00	33.51	2831.70	55.22	1718.42	54.53
Downcycle for other industries	296.40	195.17	258.90	37.89	251.30	33.42	284.90	53.94
Total	9706.46	2336.23	10,835.86	4270.28	10,775.71	4366.92	10,728.86	4731.65

Table 4 illustrates the optimal material allocation for each recovery pathway as per the model, depicting values corresponding to the assigned weightage for each objective across these scenarios.

Table 5 illustrates the total annual material recovery and the corresponding total profit achievable across different scenarios

In the base case scenario, the total recoverable material amount was 9706 MT out of 13,000 MT of fabric waste, with the total profit across all recovery pathways reaching USD 2.3 million. The material circularity in the base case scenario is 0.74.

Scenario 1

In this scenario optimized the annual material recovery and the profit generation, with a 25 % weightage attributed to profit and 75 % focused on material recovery.. Based on scenario1, the total material recoverable amounts is 10,835.86 MT from an initial 13,000 MT of fabric waste. Therefore the total material circularity of the scenario 1 is 0.83. The total profit attributed to scenario 1 amounted to USD 4.27 million. In this scenario also, the material couldn't be fully used due to capacity limits, leaving an excess that goes to landfill out. Therefore, the total amount of unprocessed material destined for landfill is indicated as 1311.5 MT.

Scenario 2

In scenario 2, the total material recovery amounts to 10,775.71 MT out of an input material quantity of 13,000 MT. The material circularity achieved in scenario 2 stands at 0.82. the profit amounting to a total of USD 4.36 million. As the other scenarios, scenario 2 also involved diverting excess material to the landfill, amounting to a total of 1357.4 MT

Scenario 3

The material recovery achieved under the optimized conditions of scenario 3 amounts to 11,225.9 MT out of the provided input of 13,000 MT. The material circularity of the scenario 3 is 0.82. Further, the optimized profit obtained through scenario 3 is USD 4.7 million. The material unpocessed in this scenario is 1405. 2 MT and this amount diverted to the landfill out.

Comparison of output value in different scenarios

Fig. 4 demonstrates that altering the weight or importance given to material recovery does not substantially affect the actual material recovery itself. Even with an increase in the weightage placed on material recovery, the change in the recovery value is minimal - it does not show a significant rise.

However, when the emphasis shifts towards assigning greater weightage to total profit instead, there's a noticeable and substantial increase in the profit value. This change happens despite a slight decrease in the material recovery. It highlights that adjusting the weightage towards prioritizing total profit leads to a much more significant increase in profit, even if it involves a small compromise on the material recovery aspect.

The findings highlight the potential for optimizing profit margins even with a marginal reduction in material recovery. Decisions can be directed based on this insight. Prioritizing profit over material recovery, considering the substantial profit increase in exchange

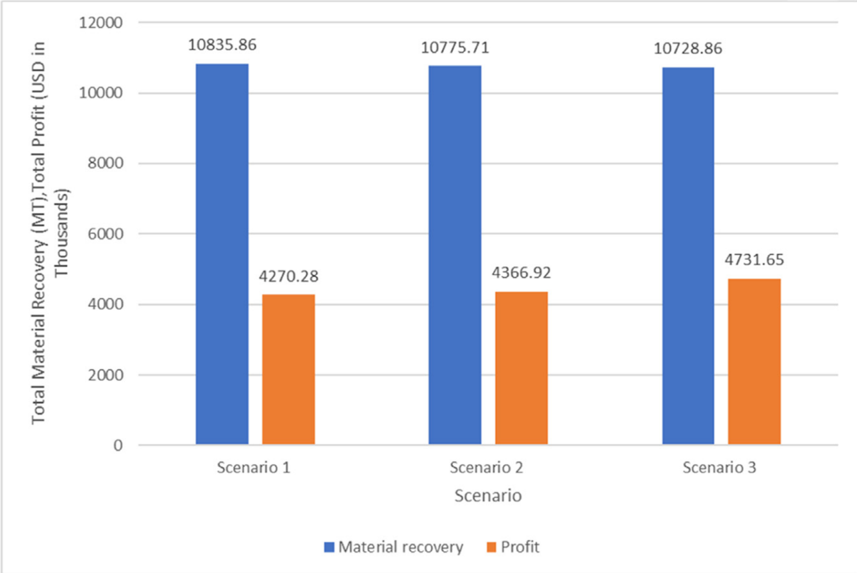

Fig. 4. Total material recovery and profit in different scenarios.

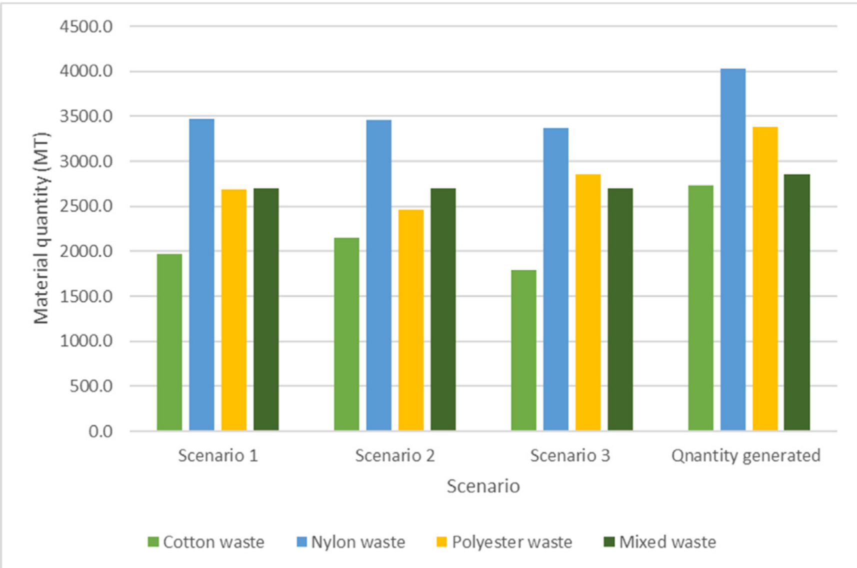

Fig. 5. Total material recovery from waste.

for a relatively minimal reduction in recovered materials, might be a sound strategic move. However, it's essential to assess the long-term implications and balance short-term gains with the company's commitment to sustainability and ethical practices. The business could potentially leverage this information to optimize profit margins while maintaining a responsible approach to material usage and recovery, ensuring a harmonious blend of financial success and environmental consciousness.

In Fig. 5, the data reveals that across all scenarios, the recovery of material from waste streams like nylon and mixed materials remains consistent. However, when the weightage assigned for material recovery is reduced, there is a small drop in material recovery from cotton waste and a slight increase in polyester recycling. This suggests that changes in weightage do not affect all waste streams in the same way. Instead, they slightly influence specific materials, causing slight variations in their recovery rates

In Fig. 6, the material recovery rates across various recovery technologies are depicted. Among these, upcycling and downcycling, exhibit low material recovery rates. Despite their existence in Sri Lanka, these recovery technologies have notably limited material processing capacities. Typically, they operate with constrained capabilities and can only handle selected material types in their processes.

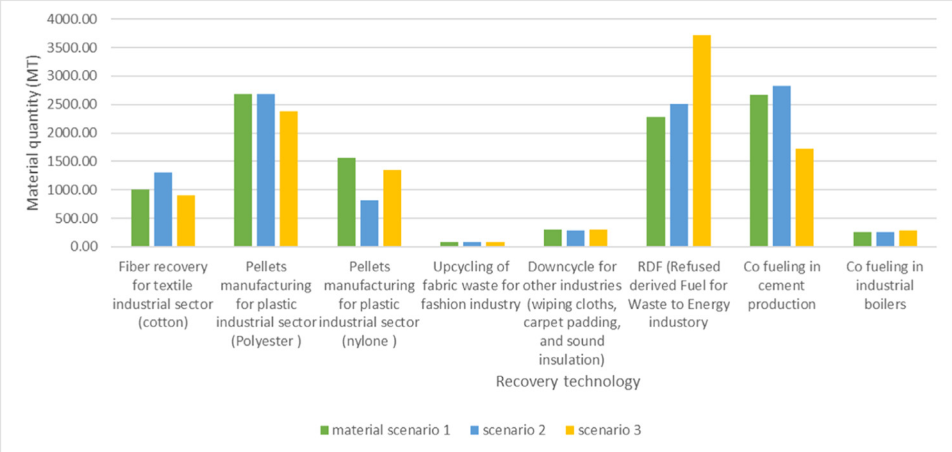

Fig. 6. Material recovery through each recovery technology.

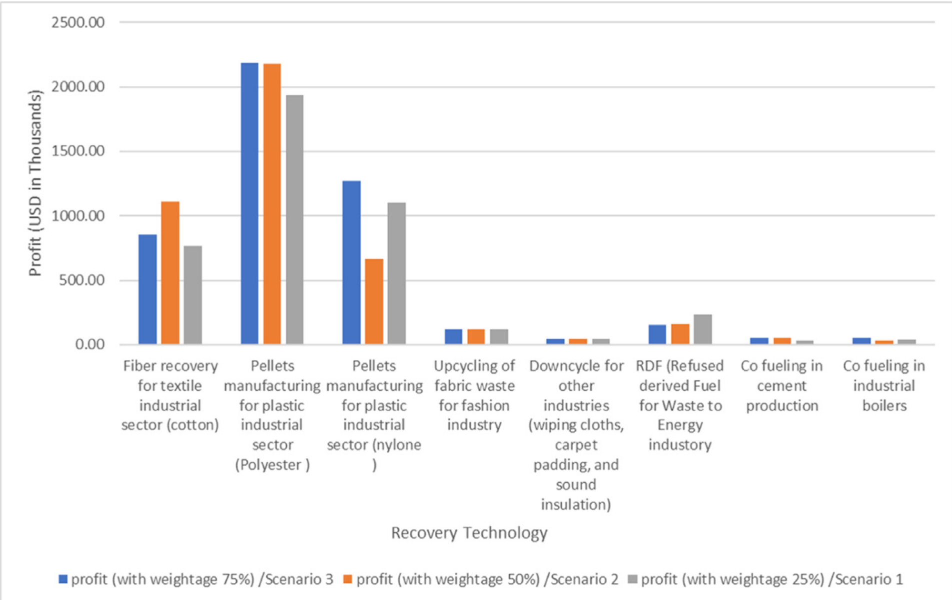

Fig. 7. Profit generation from recovery technologies.

When these limited-capacity technologies are unable to process all the waste, the remaining materials diverted to the landfill out created in the model. In the optimized conditions of all three scenarios, a fraction of materials designated for upcycling and downcycling are redirected towards the landfill out due to capacity limitation. However, when decision-makers choose one of these scenario for implementation, it's vital to adopt a strategic approach to handle the waste in the landfill out. Strengthening and enhancing the existing upcycling and downcycling channels becomes imperative to recover materials from these landfill out. This approach allows for a more sustainable management of waste by repurposing materials that would otherwise end up as linear economy pathway.

If stakeholders are considering boosting the capacities of these recovery technologies through additional recovery plant, they can utilize this model to analyze the variations in material recovery and profitability. Essentially, the model can help predict how changes in recovery technology capacities might impact the amount of material recovered and the resulting profits. This allows stakeholders to make informed decisions by simulating different scenarios and understanding their potential effects before implementing any capacity enhancements.

In Fig. 7, the total achievable profit for each recovery technology is presented, emphasizing that fiber recovery technology and the manufacturing of pellets from polyester and nylon recycling generate the highest profit values. This is mainly attributed to the high market prices of the materials recovered and recycled using these technologies, resulting in a higher profit for each unit of output, as shown in Fig. 8. The data shows that the first four recovery technologies generate more profit from their products compared to others.

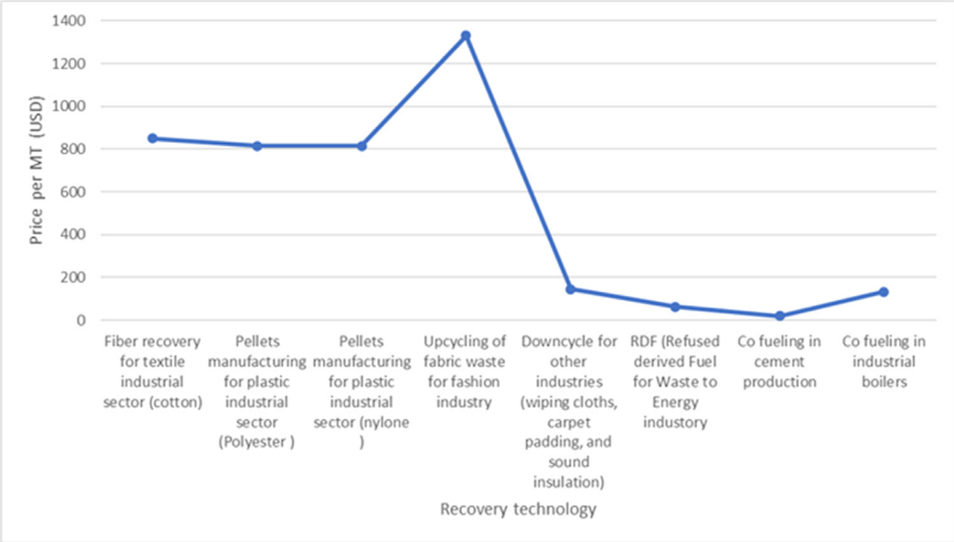

Fig. 8. Profit generation from recovery technologies.

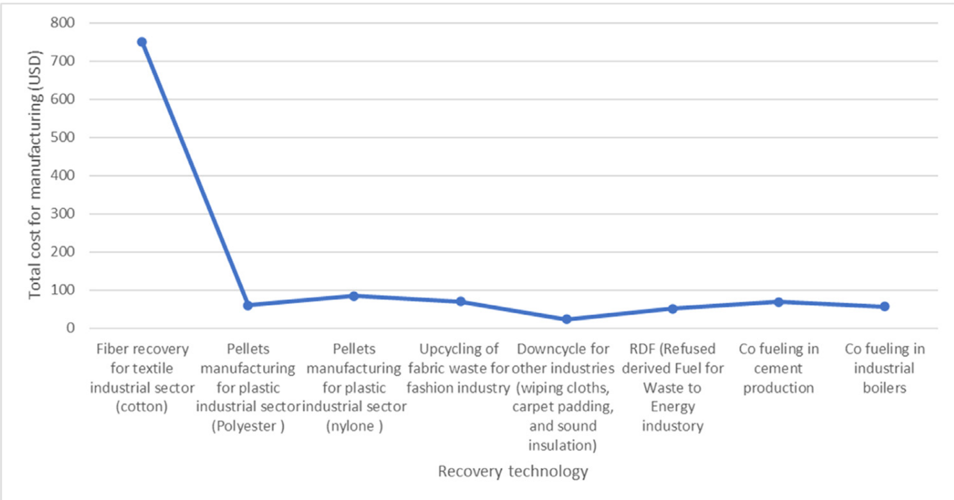

Fig. 9. Production cost per unit output.

Even though the upcycled product makes a high market price, its production is limited. It unable to go beyond a certain point, so it ends up generating lower total profits because of this production limit.

In essence, the profitability through each recovery technology is influenced by multiple factors, including the market prices of the recovered materials, total value chain cost for manufacturing and the production capacity, which directly impact the overall profit generated by each recovery technology.

In Fig. 9, the total production costs are comparatively lower for most technologies except for fiber recovery from cotton waste. This particular process does not occur in Sri Lanka; instead, the material is exported for fiber recovery, usually to Europe. Consequently, the manufacturing cost is higher due to increased transport, collection, and separation expenses. Moreover, there's a demand for cotton fabric waste in the market, necessitating its purchase from material generators, adding to the overall cost.

As a result, the fiber recovery from cotton involves a higher manufacturing cost due to a more complex value chain that extends up to the manufacturing stage. However, despite the high manufacturing cost, the recovered fiber commands a higher market price. Consequently, it generates significant profit, although not as much as the profit generated by the other two material recycling technologies: nylon recycling and polyester recycling.

If a fiber recovery plant were to exist in Sri Lanka, the manufacturing costs would notably decrease due to reduced land and sea transportation expenses. This model serves as a valuable tool for stakeholders to assess the potential profitability and variations in material recovery values under this scenario. By adjusting the input parameters - specifically, the manufacturing cost assigned to the fiber recovery pathway - and optimizing the model accordingly, stakeholders can explore different scenarios. Consequently, this flexibility allows for a comprehensive analysis of the impact of a local plant in Sri Lanka on profitability and material recovery values, offering insights into various perspectives and potential outcomes

Additionally, the polyester recycling process also is not currently operational within the country; instead, it occurs through collaboration with three Indian recovery plants. Despite this operation taking place outside the country, it does not incur substantial manufacturing costs. This is primarily due to the acquisition of polyester materials at minimal or no cost from material generators. Additionally, the transportation of these materials is facilitated through reverse logistics, significantly reducing transport expenses compared to the transportation of cotton waste to Europe. This efficient approach minimizes overall costs associated with the process, allowing for a streamlined and cost-effective polyester recycling operation despite occurring outside the country's boundaries. Upon evaluating three scenarios with varying priorities between material recovery and profit against the base case, it becomes evident that the optimized scenarios exhibit higher circularity values compared to the base case. Additionally, the optimization model yields increased profits. This robust demonstration underscores the effectiveness of this model in decision-making, offering comprehensive insights across diverse perspectives. The model's robustness is evident, showcasing its adaptability and applicability across various contexts, thereby emphasizing its versatility in decision support. Here, we allocate weightage to the total annual material recovery and total annual profit. However, there's flexibility to assign weightages to individual recovery technologies based on their circularity values, or weightages for profit concerning specific technologies. This flexibility allows us to explore how the results might vary based on these different perspectives. The model accommodates multiple approaches, enabling us to obtain diverse outcomes and insights from various angles

The decision-making tool's flexibility allows stakeholders to assign different weightages to recovery and profit based on specific contexts. By adjusting these parameters, the model can explore various scenarios, providing comprehensive insights and diverse outcomes. This adaptability ensures that the tool can support decision-making across different waste streams, making it a valuable asset for optimizing waste management strategies in various industries and regions

Despite the valuable insights provided by the decision-making tool, several research limitations must be acknowledged. The model's accuracy is contingent upon the availability and quality of input data, which can vary significantly across regions and waste streams, potentially limiting its generalizability. Additionally, while the model is designed for versatility, the unique behaviors and properties of different waste streams may require specific adjustments, and the rapidly changing technological landscape can impact its relevance. Economic factors such as market price fluctuations and regional regulatory frameworks, which the model does not fully account for, also pose significant challenges. Furthermore, the model focuses primarily on economic factors, potentially overlooking environmental and social considerations crucial for long-term sustainability. Operational assumptions about efficiency and logistics may not always hold true, and scaling up strategies may encounter practical implementation barriers. To enhance the model's robustness, future research should integrate more comprehensive data, incorporate environmental and social impacts, and regularly update to reflect technological and market changes, supported by real-world pilot projects and case studies.

In conclusion, our study underscores the imperative shift towards sustainable waste management practices, particularly in the industrial sector, driven by escalating environmental regulations and policy frameworks worldwide. The introduction of a novel optimization model, tailored to identify optimal material circularity routes, marks a significant stride towards achieving the goals of the circular economy. Our model, integrating Genetic Algorithm optimization within MATLAB, prioritizes both material recovery and profit generation, thereby ensuring a balanced approach to environmental sustainability and economic viability. Through its application to fabric waste generated by the Biyagama Export Processing Zone, we have demonstrated its efficacy as a practical decision-making tool for stakeholders in the waste management sector.

Our findings reveal that altering the weight or importance given to material recovery does not substantially affect the actual material recovery itself. Even with increased emphasis on material recovery, the change in the recovery value is minimal. However, shifting the focus towards total profit leads to a noticeable and substantial increase in profit, despite a slight decrease in material recovery. This highlights that prioritizing profit can yield significant economic gains with only minor compromises on recovery efficiency. Additionally, our results indicate that different waste streams respond uniquely to changes in weightage, necessitating tailored approaches for optimal outcomes.

We also found that the success of material recovery hinges upon the efficiency of recovery technologies and plant capacities, as well as considerations of market prices and manufacturing costs. For instance, upcycling and downcycling technologies, despite their low material recovery rates and limited capacities, play a critical role in reducing landfill contributions. Enhancing these technologies and considering local recovery options, such as establishing a fiber recovery plant in Sri Lanka, could significantly reduce costs and improve profitability.

Recognizing the research limitations, including data specificity, technological constraints, and economic fluctuations, future research should focus on enhancing data quality, incorporating environmental and social impacts, and validating the model through real-world applications. By addressing these challenges, the model's robustness and relevance can be further improved, providing a more comprehensive decision-making tool for waste management.

Overall, our research bridges a critical gap in sustainable waste recovery pathways, offering a scalable solution poised to advance the circular economy agenda in the industrial sector. By integrating environmental and economic objectives, our model provides a holistic framework for stakeholders to navigate the complexities of waste management, fostering a transition towards a more sustainable and profitable future.

Supplementary material and/or additional information [OPTIONAL]

Not applicable.

For a published article

Not applicable.

Limitations

Not applicable.

Ethics statements

No ethical considerations were required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

L.G.L.M. Edirisinghe: Conceptualization, Methodology, Data curation, Writing – original draft, Formal analysis, Validation, Visualization. **A.A.P. de Alwis:** Supervision, Conceptualization, Methodology. **S. Prakash:** Software, Validation, Visualization, Writing – review & editing. **M. Wijayasundara:** Supervision, Conceptualization, Methodology.

Data availability

Data will be made available on request.

Acknowledgments

We acknowledge the staff of Biyagama export processing zone who has direct or indirect supported this research.

References

[1] H.N. Arosha, A.A.P Alwis, L.G.L.M Edirisinghe, A method for determining the recycling value of unprocessed municipal solid waste in one cubic meter waste composition analysis technique, MethodsX. 12 (2024) 102626–102626, doi:10.1016/j.mex.2024.102626.
[2] David, A., Devi Thangavel, Y., & Sankriti, R. (2019). Recover, recycle and reuse: an efficient way to reduce the waste. https://www.tjprc.org/publishpapers/2-67-1554700771-4IJMPERDJUN20194.pdf
[3] L.G.L.M. Edirisinghe, A.A.P.de Alwis, S. Prakash, M. Wijayasundara, N.A. Arosha Hemali, A volume-based analysis method to determine the economic value of mixed industrial waste, Clean. Environ. Syst. 11 (2023) 100142, doi:10.1016/j.cesys.2023.100142.
[4] L.G.L.M. Edirisinghe, A.A.P. de Alwis, M. Wijayasundara, N.A. Hemali, Quantifying circularity factor of waste: assessing the circular economy potential of industrial zones, Clean. Environ. Syst. 12 (2024) 100160, doi:10.1016/j.cesys.2023.100160.
[5] Ellen MacArthur Foundation, 2023 (accessed on November 1, 2023) https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview#:~:text=The%20circular%20economy%20is%20a.
[6] Y.A. Hajam, R. Kumar, A. Kumar, Environmental waste management strategies and vermi transformation for sustainable development, Environ. Challenges 13 (2023) 100747, doi:10.1016/j.envc.2023.100747.
[7] A. Hendriks, Temporality in visions of desirable futures: Chronos and Kairos in the case of the circular economy on Gotland, J. Clean. Prod. 439 (2024) 140733, doi:10.1016/j.jclepro.2024.140733.
[8] J. Kirchherr, R. van Santen, Research on the circular economy: a critique of the field, Resour. Conserv. Recycl. 151 (2019) 104480, doi:10.1016/j.resconrec.2019.104480.
[9] Macias Aragonés Marta, Arroyo Torralvo Fátima, How to select the best approach for circular economy assessment? 3D positioning framework, decision support tool and critical analysis for bio-based systems, Environ. Impact. Assess. Rev. 106 (2024) 107493–107493, doi:10.1016/j.eiar.2024.107493.
[10] J. Tang, Q. Wang, G. Choi, Efficiency assessment of industrial solid waste generation and treatment processes with carry-over in China, Sci. Total Environ. 726 (2020) 138274, doi:10.1016/j.scitotenv.2020.138274.
[11] H.N. Tran, N.B. Nguyen, N.H. Ly, S.W. Joo, Y. Vasseghian, Core-shell Au@ZIF-67-based pollutant monitoring of thiram and carbendazim pesticides, Environ. Pollut. 317 (2023) 120775, doi:10.1016/j.envpol.2022.120775.
[12] V. Yasser, A. Monireh, D. Elena-Niculina, C. Sonne, A global meta-analysis of phthalate esters in drinking water sources and associated health risks, Sci. Total Environ. 903 (2023) 166846–166846, doi:10.1016/j.scitotenv.2023.166846.