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Mathematical Programming-Based Approach for Recycling Technology Allocation in Textile Waste Systems

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This study develops the Waste-Recycling Technology Allocation Pathways (WTAP), a linear programming (LP) model that optimizes textile waste allocation across mechanical, chemical, non-woven, and landfill technologies within reverse logistics networks (RLNs). The model minimizes carbon footprint while maximizing waste to technology allocation. WTAP incorporates four textile waste types that include pre-consumer, post-consumer, side-stream, and throwback waste to represent both closed- and open-loop pathways. Two case studies that applied a functional unit of 34,088 t/y of recyclable textile waste evaluate 100 % cotton waste and cellulose-rich blended waste. Case 1 allocated 44 % of cotton waste to mechanical recycling and 56 % to non-woven process that results in 0.76 tCO_2-eq/t waste processed. Case 2 distributes blended waste across chemical recycling at 29 %, mechanical recycling at 15 %, and non-woven process at 56 % that yields 1 tCO_2-eq/t waste processed. These results demonstrate the importance of technology-material matching in reducing environmental burdens. WTAP supports data-driven decision-making for sustainable textile waste management and circular economy policy compliance.

1. Introduction

The textile industry follows a linear production model that generates substantial material waste. Regulatory initiatives respond to these by promoting circularity through reverse logistics networks (RLNs) that enable the recovery of end-of-use (EOU) and end-of-life (EOL) textiles through recycling or reuse. Mathematical programming models support this transition by optimizing system performance across collection, sorting, transportation, and treatment stages based on defined objectives. The study of İşeri and Kızılaslan (2024) used a linear programming model that aligned pre-consumer textile offcuts with garment production patterns and achieved 57–87% reuse of end-of-roll fabrics. Rouhani et al. (2024) developed a tri-objective model that incorporated EOU and EOL returns using possibility-based programming with hexagonal fuzzy numbers and optimized economic, environmental, and social outcomes. Their results showed that EOU waste posed more complex sustainability impacts than EOL waste. Singh and Goel (2024) proposed a mixed-integer linear programming model that allocated pre- and post-consumer waste under inflation-adjusted costs and optimized facility locations and processing flows. Ezhilarasan and Mishra (2022) modeled a circular supply chain that minimized emissions, wastewater, and residuals. Abbas-Abadi et al. (2025) presented a framework that emphasized the alignment of textile waste types with recovery technologies to improve output quality and environmental performance. However, most models apply uniform recycling methods and fail to consider open-loop or closed-loop options treatment for textile waste. This limits the ability to evaluate material-technology compatibility constraints for these type of waste. The European Environment Agency (2023) also identified that side-stream and throwback waste as ideal for recycling due to their uniform composition and clear traceability as key attributes. Excluding these factors from existing models limits their alignment with Extended Producer Responsibility (EPR) policies and highlights a critical gap in current research.

This study addresses this research gap by developing the Waste-to-Technology Allocation Pathway (WTAP) model. WTAP is an LP that allocates four waste streams (side-stream, pre-consumer, post-consumer, throwback) across four treatment technologies (mechanical, chemical, non-woven, landfill) to minimize carbon footprint. The novelty lies in its granularity, inclusion of underutilized streams, and differentiation of open- vs.

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closed-loop outcomes. It is tested via two case studies: 100 % cotton and cellulose-rich blends. A five-year planning horizon was adopted in the study. This is based on the study of Zhang et al. (2025) that reflects infrastructure rollout periods in textile waste systems and aligns with regulatory timelines under circular economy and EPR policies identified by Sandin et al. (2025). WTAP thus provides a scientifically grounded and operationally viable model for advancing textile circularity. The paper is organized as follows. The problem is formally defined in Section 2. The modelling framework is described in Section 3 and demonstrated on two case studies in Section 4. Conclusions, general implication, and future research directions are discussed in Section 5.

2. Problem Statement

The formal problem statement for this study is elaborated as follows.

- Given a set of textile waste sources $i \in I$ that is classified as Side-Stream (SS), Pre-Consumer (PrC), Post-Consumer (PsC), or Throwback (TB) is characterized by an annual waste flow FR_i (t/y) and a corresponding volume of unrecyclable waste UR_i (t/y).
- Given a set of sinks $j \in J$ that represents a treatment technology classified as mechanical recycling (MECH), chemical recycling (CHEM), non-woven processing (NWOV), or landfill (LANDF) is defined by an annual capacity C_j (t/y) and carbon footprint EF_j (tCO_2-eq/ t waste processed) generated by each treatment process.
- Given A_{ij} as the quantity of textile waste (t/y) allocated to the sinks $j \in J$, originating from the annual waste flow FR_i (t/y) in the waste sources $i \in I$.
- The sink j generates an output SA_j (t/y) that represents the surplus waste eligible for yarn spinning and is defined as the difference between the total allocated waste and the minimum required weaving input W_j (t/y). From this, the amount of fiber available for blending $WOVEN_j$ (t/y) with virgin cotton is denoted by $VCALLOC_j$ (t/y).
- Given a set of treatment sinks $j \in J$ that is associated with a spinning-compatible technology $t \in T$ is identified by a binary parameter Y_{jt} that equals 1 when sink j supports yarn spinning under condition t. The total spinning-eligible surplus SA_j from sinks that meet this condition is constrained by a global limit $SPIN$ (t/y) that bounds cumulative output and a local spinning cap $SMAX_j$ (t/y).

The problem is to determine the optimal allocation of textile waste across various treatment technologies that minimizes the carbon footprint generated. Figure 1 illustrates feasible closed- and open-loop pathways. The model assumes deterministic, steady-state conditions over a five-year horizon and is formulated as a linear program.

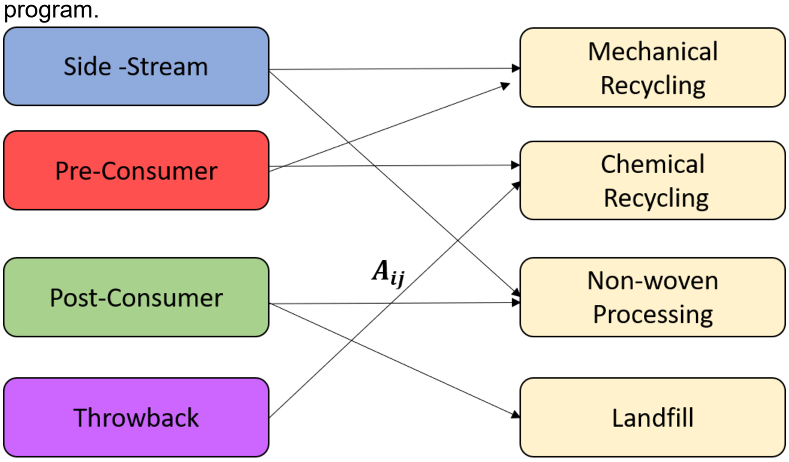

Figure 1: Textile waste-technology allocation superstructure

3. Optimization Model

The model aims to minimize total carbon footprint from textile waste processing as Eq(1).

$$\sum \quad min\ Z = \sum_{i \in I} \sum_{j \in J} A_{ij} \cdot EF_j \qquad (1)$$

This equation quantifies CO_2 equivalent emissions based on the volume of waste allocated and the carbon footprint associated with each treatment technology. Two fundamental constraints are imposed to ensure model feasibility. Eq(2) enforces a source flow limit that restricts the combined total of allocated waste and unrecycled waste from each source to its available supply. Eq(3) sets a sink inflow constraint that limits the total allocation to each sink to its defined processing capacity. These constraints uphold mass balance and operational integrity that maintain realistic and technically viable material flow within the textile waste RLN.

$$\sum_{i\epsilon I} A_{ij} + UR_i \leq FR_i \qquad \forall i \in I \qquad (2)$$

$$\sum_{i\in I} A_{ij} \leq C_i \qquad \forall j \in J \qquad (3)$$

Eq(4) to Eq(10) define the core allocation logic and feasibility constraints in the textile waste recovery model. Eq(4) calculates the spinning-eligible surplus SA_j at each sink j as the difference between the total allocated waste $\sum_{i\in I} A_{ij}$ and the required weaving input W_j . Eq(5) ensures that waste is allocated only to sinks assigned a compatible treatment technology that maintains consistency between flow and spinning potential as indicated by the binary variable Y_{jt} across technology-spin mappings $t \in T$. This equation ensures a large upper bound M for the total flows in all sources. Eq(6) limits the total surplus $\sum_j SA_j$ to the system-wide spinning capacity $SPIN$, while Eq(7) enforces a local cap $SMAX_j$ for each sink. Eq(8) ensures that the total allocated waste across all sources meets a minimum recovery threshold VC that supports operational viability. Eq(9) refines this by allowing only allocations from woven-compatible sinks $WOVEN_j$ to count toward virgin cotton blending $VALLOC_j$. Eq(10) enforces non-negativity of allocation flows.

$$\sum_j SA_j = \sum_{i\in I} A_{ij} - W_j \qquad \forall j \in J \qquad (4)$$

$$\sum_{i\in I} A_{ij} \leq M \cdot \sum_{t\in T} Y_{jt} \qquad \forall j \in J \qquad (5)$$

$$\sum_{j\in J} SA_j \leq SPIN \qquad (6)$$

$$SA_j \leq SMAX_j \qquad \forall j \in J \qquad (7)$$

$$\sum_{i\in I} \sum_{j\in J} A_{ij} \geq VC \qquad (8)$$

$$VCALLOC_j \leq VC * WOVEN_j \qquad \forall j \in J \qquad (9)$$

$$A_{ij} \geq 0 \qquad \forall i \in I,\ j \in J \qquad (10)$$

4. Case Study 1

This case study evaluates the recycling of 100% cotton textile waste using a functional unit of 34,088 t/y that represents the total mass of recyclable textile waste processed through mechanical, chemical, and non-woven technologies. The 24 % landfill cotton share from Lu et al. (2022) study was used to estimate total cotton waste and allocate it across PrC, SS, and PsC stages. PrC waste was estimated by applying a 5 % cutting loss (Domina and Koch, 2002) to 2017 garment exports reported by PSA. Reports on spinning loses from Karthik and Gopalakrishnan (2014) were used to estimate SS waste from the annual cotton yarn production. PsC waste was quantified from 2017 cotton garment import volumes and YouGov (2019) discard (46 %) and landfill rates (40 %). Fibers recovered through mechanical and chemical recycling were blended with 80 % virgin cotton before spinning, enhancing fiber circularity.

Tables 1 and 2 present the empirical data and literature-based assumptions used in the case study. Zero values in Table 1 indicate complete recycling, while zeroes in Table 2 reflect unutilized pathways. Foreground inventory data from peer-reviewed studies were scaled to the functional input of 34,088 t/y of recyclable cotton waste. The mechanical recycling data on energy use and fiber yield were sourced from Espinoza-Pérez et al. (2024) and Roy et al. (2023); chemical recycling inputs and emissions from Fidan et al. (2021) and Hammar et al. (2024); and non-woven processing data from Karmakar et al. (2025). Batch size and throughput scaling factors were drawn from Esteve-Turrillas and Guardia (2017) and Rosson and Byrne (2020). The scaled values were incorporated in the LCA study conducted in SimaPro 9.5 to determine the carbon footprint per technology and integrate it as environmental parameter in the LP model solved in LINGO 19.0 that achieved convergence on a 2.2 GHz, 16 GB RAM system.

Table 1: Textile waste sources in Case Study 1

Source	Flow Rate (t/y)	Unrecycled (t/y)
Side-Stream (SS)	0.26	0
Pre-Consumer (PrC)	1.27	0
Post-Consumer (PsC)	87,100	64,454
Throwback (TB)	44,000	32,560

Table 2: Textile waste sinks in Case Study 1

Sink	Capacity (t/y)	Carbon Footprint (tCO_2eq/t)	Spinning Capacity (t/y)
Mechanical Recycling	90,000	64	90,000
Chemical Recycling	100,000	305	10,000
Non-woven	20,000	350	0

Figures 2a and 2b present the optimized allocation results for Case Study 1 that involves 34,088 t of recyclable pure cotton textile waste. Mechanical recycling processes 11,440 t from Throwback (TB) waste and 3,560 t from Post- Consumer (PsC). The non-woven process handles 19,088 t, comprising 19,086 t from Post-Consumer (PsC), 1.27 t from Pre-Consumer (PrC), and 0.26 t from Side-Stream (SS) sources. No allocation is made to chemical recycling or landfill. The optimization results in a total carbon footprint of 0.76 tCO_2-eq/t waste processed. With 44 % directed to mechanical and 56 % to non-woven processing. This configuration reflects a sustainability-driven strategy favoring low-impact recovery tailored to pure cotton textile waste through full landfill diversion and no chemical treatment.

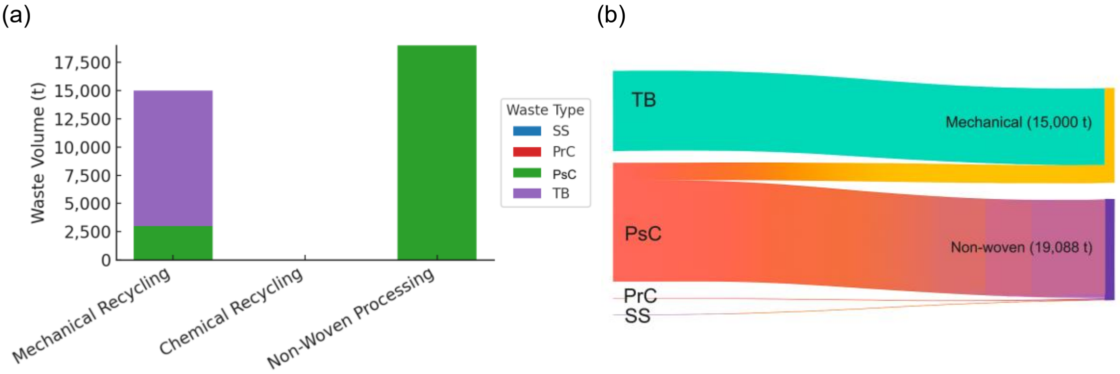

Figure 2: Optimal WTAP for Case 1 showing volume by technology (a) and Sankey flow paths (b)

5. Case Study 2

This illustrative study follows the same scenario as Case Study 1 but focuses on textile waste composed of cellulose-rich fibers blended with other materials. Due to the difficulty of recycling blended fibers mechanically, chemically recycled fiber volumes are higher (Hammar and Hanning, 2024). Waste distribution for Case Study 2 is shown in Tables 1 and 3. Zero values in Table 3 indicate that specific recycling sinks were not utilized in the optimized allocation. Carbon footprint in Table 3 was calculated using the same LCA method in SimaPro 9.5 as in Case Study 1. Pilot-scale treatment capacities for Case 2 were based on literature benchmarks cited in the previous case.

Table 3: Textile waste sinks in case Study 2

Sink	Capacity (t/y)	Carbon Footprint (tCO_2eq/t)	Spinning Capacity (t/y)
Mechanical Recycling	30,000	64	5,000
Chemical Recycling	100,000	305	90,000
Non-woven	20,000	350	0

The optimized results for Case Study 2 (Figures 3a and 3b) allocate 34,088 t of recyclable cellulosic-rich blended textile waste across three end-of-life technologies. Non-woven processing accounts for 56 % (19,088 t) mainly sourced from post-consumer inputs (19,086 t). Throwback (TB) waste is divided between mechanical recycling (5,000 t; 15 %) and chemical recycling (10,000 t; 29 %). This highlights the role of chemical pathways in handling fiber blend complexity. No allocation is made to the landfill. The optimization yields a total carbon footprint of 1 tCO_2-eq/t waste processed. These results quantitatively demonstrate a high material recovery rate and the strategic deployment of chemical recycling to optimize the valorization of cellulosic-rich textile waste.

(a) (b)

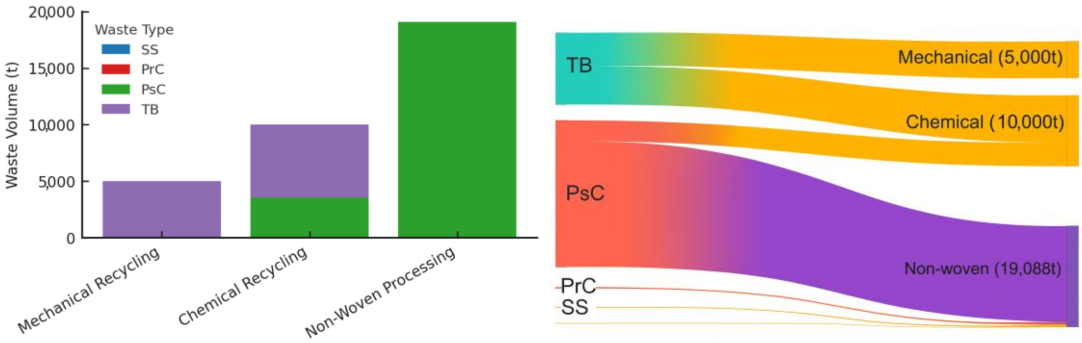

Figure 3: Optimal WTAP for Case 2 showing volume by technology (a) and Sankey flow paths (b)

The comparative analysis of WTAP's Case 1 and Case 2 highlights quantifiable trade-offs between environmental performance and technological suitability in textile waste recycling. Optimization of pure cotton waste yields a carbon footprint of 0.76 tCO_2-eq/t waste processed by allocating 15,000 t (44 %) to mechanical recycling and 19,088 t (56 %) to non-woven processing. Optimization of cellulosic-rich blended waste allocates 10,000 t (29 %) to chemical recycling, 5,000 t (15 %) to mechanical, and the remainder to non-woven. This yields a carbon footprint of 1 tCO_2-eq/t waste processed. This value is 31.6 % higher than Case 1. This aligns with European Environment Agency (2023) benchmarks of 0.90–1.20 tCO_2-eq/t waste for chemical recycling and supports Khan et al. (2025), who report 0.52–0.78 tCO_2-eq/t waste for mechanical recycling. Abagnato et al. (2024) similarly report 40–55 % lower emissions for mechanical recycling. These findings underscore the importance of quantitatively evaluating trade-offs between carbon footprints and material quality in open-loop versus closed-loop recycling systems.

6. Conclusions

This study developed the Waste Textile Allocation Plan (WTAP) for optimizing textile waste allocation across recycling and recovery pathways to minimize carbon footprints. WTAP supports decision-making by linking different types of waste to suitable treatment technologies and evaluating trade-offs between material recovery and carbon emissions. The model assumes steady-state conditions over a five-year period and does not consider seasonal changes, user behavior, or uncertainty in waste supply and processing capacity. These limitations can be addressed through scenario-based or stochastic approaches. Fixed emission factors limits the changes in energy sources or fiber content. Future improvements should include updated life cycle data, spatial mapping of treatment infrastructure, and sensitivity analysis. These additions would improve the model's accuracy and make it more adaptable to regional applications in circular textile waste management.

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