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# Analysis of the Impact of Skywalker Drone Battery Waste Management on the Environment Using Linear Programming Method

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ABSTRACT: The disposal of lithium-based drone batteries presents a significant environmental challenge due to the presence of heavy metals and hazardous substances. Effective management strategies are essential to reduce pollution and mitigate operational risks associated with improper handling. This study proposes an optimal waste management strategy for Skywalker drone batteries using a Linear Programming (LP) approach. The model incorporates three waste management options: recycling, temporary storage, and final disposal. It also accounts for facility capacity limitations, environmental regulations, and cost constraints. The simulation results demonstrate that the LP model provides an optimal waste allocation scheme. Compared to conventional waste management methods, the LP-based strategy reduces environmental impact and achieves higher cost efficiency. The findings highlight the effectiveness of LP modeling as a decision-support tool for waste management planning. The study recommends the adoption of an LP-based integrated management framework to support future environmental and operational decisions in drone technology.

**KEYWORDS:** Lithium battery waste; Skywalker drone; waste management; linear programming (LP); cost optimization

## 1. Introduction

The waste problem has become a pressing national issue due to rapid population growth, advancing technology, and changing lifestyles [1]. This trend has led to a significant increase in both the volume and variety of waste in different regions. Managing this waste demands substantial financial resources and land area. If left unmanaged or improperly handled, waste can pose serious threats to human health and the environment. Existing waste management practices in Indonesia still rely heavily on an end-of-pipe approach, which primarily involves transferring waste from one site to another, such as from temporary storage to final disposal sites (TPS or TPA). If this linear approach continues, waste accumulation will soon exceed the Earth’s capacity to absorb it [2].

In urban centers worldwide, the escalating volume of waste is becoming increasingly difficult to manage. Without effective systems, this growth not only burdens municipal infrastructure but also accelerates environmental degradation and public health risks. In contrast, well-designed waste management strategies can yield both economic and environmental benefits [3]. One emerging issue is the management of lithium battery waste. Lithium batteries are now widely used as energy storage in electronic devices, renewable energy systems, and electric vehicles. These batteries rely on raw materials obtained through natural mining processes, which are non-renewable and have limited global reserves. Skywalker drones, which are the focus of this study, also use lithium-based batteries, adding to the growing concern [4].

The use of Skywalker drones is increasing rapidly across various sectors, including photography, agriculture, surveillance, and mapping. This widespread adoption leads to the accumulation of Lithium Polymer battery waste, which contains heavy metals and toxic chemicals. When improperly disposed of, such waste can contaminate soil, water, and air, ultimately threatening ecosystems and public health [1, 5]. Despite these risks, public awareness and concern regarding lithium battery waste remain low in Indonesia. Uncontrolled disposal of battery waste can contribute to serious health issues, including carcinogenic effects. This underscores the urgent need for a sustainable, effective waste management solution [2, 6].

To address this gap, this study introduces an urban mining framework tailored to lithium drone battery waste management in the Indonesian context. Urban mining focuses on recovering valuable materials from waste streams, thereby reducing environmental harm while creating economic value. Although previous studies have identified the potential of urban mining in extracting economically valuable materials from used lithium batteries, few have translated this concept into a structured, decision-support model that can be applied in real-world waste management planning [7].

This study offers a novel approach by integrating urban mining with Linear Programming to optimize key stages of the waste management process, including collection, sorting, recycling, and final disposal [3]. The novelty lies in the application of a quantitative method that systematically evaluates critical factors such as cost, distance, and environmental impact to identify the most efficient and sustainable strategies. The aim of this study is to develop a decision-making model that not only minimizes environmental risks and logistical costs but also maximizes resource recovery and long-term sustainability.

## 2. Materials and Methods

### *2.1. Data collection and preparation.*

The study begins with a comprehensive data collection process. This includes gathering information on the total quantity of battery waste generated, the composition of the batteries, overall waste volume, associated management costs, and relevant environmental parameters. These data form the basis for modeling and evaluating various waste management strategies.

### *2.2. Formulation of the linear programming model.*

After data collection, a Linear Programming (LP) model is developed to represent the battery waste management system mathematically. This model incorporates specific decision variables and objective functions, providing a structured approach to balance competing factors such as cost efficiency and environmental sustainability. A key step in this process is identifying decision variables. In this study, the variables represent strategic decisions such as the amount of waste allocated for recycling, the volume directed to landfills, the portion processed using thermal or chemical treatment methods, and the selection of appropriate waste management facility locations. These variables are designed to reflect realistic management options and constraints [8].

### 2.3. *Optimization process.*

The formulated model and data are processed using optimization software. The goal is to identify the most effective waste management strategy that minimizes cost, reduces environmental harm, and operates within existing constraints. The resulting solution is compared with the current waste management practices to evaluate improvements in sustainability and performance.

### 2.4. *Environmental impact evaluation*.

Once the optimal solution is identified, its environmental impact is assessed relative to existing conditions. This step helps determine the extent to which the proposed strategy can reduce environmental degradation and support long-term sustainability in battery waste management.

### 2.5. *Linear programming analysis.*

The optimization analysis uses a linear programming model with the simplex method. The simplex method is suitable for solving both simple and complex linear programming problems involving multiple variables [9].

The general structure of the linear program used in this study includes the following:

Objective function:
$\text{Maximize or Minimize } Z = \sum Cj\, Xj$

Subject to constraints:
$\sum aij\, Xj \leq bi, \text{ for all } i$
$Xj \geq 0, \text{ for all } j$

In this model, Xj represents the decision variables associated with different types of battery waste treatment activities. Cj refers to the cost or benefit coefficient assigned to each activity, indicating its contribution to the objective function. aij indicates the amount of a specific resource required to carry out activity j under constraint i, while bi denotes the total available amount of each resource. The overall objective is to optimize Z, which represents the total value to be either minimized in terms of cost or maximized in terms of benefit, depending on the goal of the model.

The model is designed to optimize the management of lithium battery waste generated by Skywalker drones by determining the best allocation of available resources across different treatment options.

### *2.6. Research objective and evaluation indicators.*

The primary objective of this study is to develop an efficient and effective strategy for managing lithium battery waste generated by Skywalker drones. The proposed model is designed to minimize management costs, optimize the use of available resources, and promote environmentally sustainable treatment methods. To assess the success of the model and the proposed strategies, several performance indicators are used. These include the reduction of environmental impact by minimizing pollution and ecological risks associated with improper battery disposal, improvement in operational efficiency through lower costs, higher recycling rates, and better resource utilization, and the implementation of model-based policy recommendations in actual waste management practices. Together, these indicators provide a comprehensive framework for evaluating the environmental, economic, and social benefits of the optimized waste management strategy.

## 3. Results and Discussion

### *3.1. Drone battery waste composition and environmental risks.*

Drone battery waste contains harmful chemicals that can seriously pollute the environment if not properly managed. Effective management is essential not only to mitigate environmental risks but also to recover valuable materials such as nickel and cobalt through hydrometallurgical recycling processes [11]. In this study, a linear programming approach is employed to optimize the allocation of battery waste across different management pathways, based on both environmental and economic criteria. The model in this study distributes battery waste into three key management pathways: recycling, safe disposal, and temporary storage. Each plays a vital role in ensuring environmental protection and resource recovery. Recycling is central to this strategy, as it enables the recovery of valuable metals from used batteries. This reduces the need for new raw material extraction and lowers the environmental footprint associated with battery production and disposal. Through this process, waste batteries can be transformed into reusable components, supporting a circular economy and minimizing the generation of hazardous waste. Safe disposal is essential for batteries that are no longer suitable for recycling due to advanced degradation or contamination. This process involves treating waste to neutralize toxic substances or isolating it in specialized facilities to prevent leaching into soil and water, thereby protecting both ecosystems and human health.

Temporary storage acts as a transitional phase between battery collection and final processing. It ensures that used batteries are kept in a secure, controlled environment to prevent hazards such as leaks or fires. Maintaining appropriate storage conditions is critical to preserving the integrity of the batteries until they are ready for recycling or safe disposal. These three pathways form an integrated and sustainable approach to battery waste management, combining safety, environmental responsibility, and resource efficiency. The objective function of the linear programming model is to minimize the total environmental impact, measured through emissions and hazardous waste production. This is subject to capacity constraints for each management pathway and the total amount of waste available for processing. The parameters for this model are based on studies examining the characteristics of lithium-ion battery waste and the performance of hydrometallurgical recycling processes [12]. Analytical results from this research revealed that Skywalker drone battery waste contains approximately 15% nickel (Ni), 10% cobalt (Co), and trace amounts of hazardous elements such as lead (Pb) and cadmium (Cd) [13]. The optimal parameters for the recycling process involve the use of sulfuric acid with added hydrogen peroxide ($H_2O_2$), conducted at a temperature of 90°C for 90 minutes, with a stirring speed of 300 revolutions per minute [13]. The results of the linear programming model and the optimal allocation of battery waste are illustrated in Figure 1.

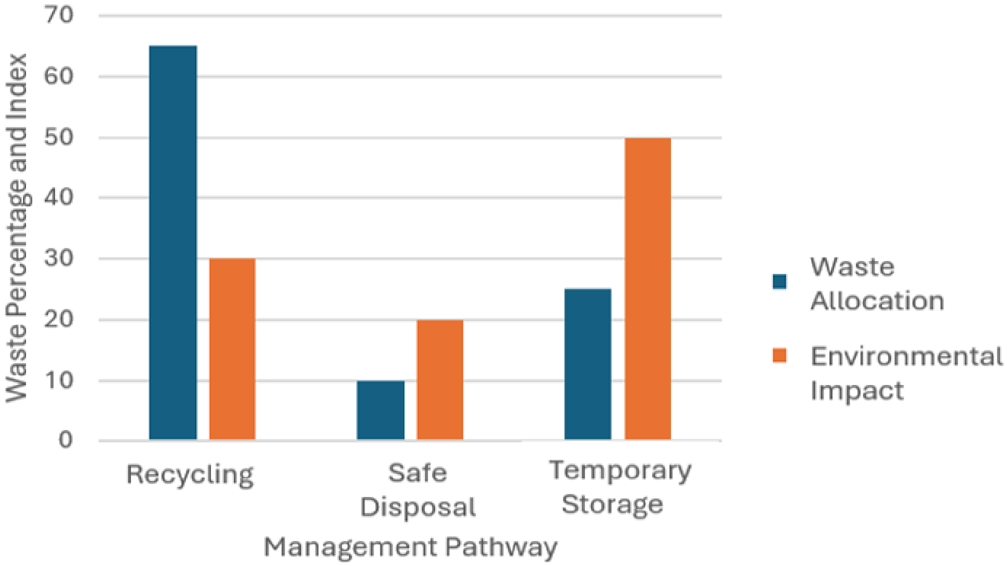

**Figure 1.** Waste allocation and environmental impact.

Recycling emerges as the preferred management pathway due to its low environmental impact and ability to recover valuable metals. Among the three available options—recycling, safe disposal, and temporary storage—recycling offers the highest potential for resource recovery and the lowest pollution risk. However, its capacity is limited by the availability of infrastructure and the high operational costs, preventing 100% of the waste from being allocated to this line. These optimization results align with previous research, which has demonstrated the effectiveness of hydrometallurgical processes in recovering metals while minimizing ecological damage [14]. The use of linear programming in this context enables a balanced allocation that considers both environmental priorities and technical limitations [15]. This framework offers actionable insights for policymakers and waste management authorities in developing sustainable strategies for drone battery waste.

The model optimally allocates Skywalker drone battery waste with a primary emphasis on recycling, thereby minimizing environmental risks while maximizing the reuse of valuable materials such as nickel and cobalt. To ensure successful implementation, the study recommends investments in recycling facility development and broader educational outreach on battery waste management practices. The management of Skywalker drone battery waste is of critical concern due to the presence of hazardous and heavy metals that pose significant environmental risks if not properly handled. Lithium battery waste is categorized as B3 waste (Hazardous and Toxic Materials), requiring special treatment and regulatory compliance [16].

### *3.2. Optimization of battery waste allocation using linear programming.*

This study applies a linear programming approach to allocate battery waste across three pathways—recycling, safe disposal, and temporary storage—with the goal of minimizing environmental impact. The model uses pollution parameters as key decision variables to guide this allocation. The primary environmental indicators considered include the concentration of heavy metals such as nickel (Ni), cobalt (Co), lead (Pb), and cadmium (Cd) found in liquid waste and surrounding soil. In addition, water quality parameters like pH, Total Dissolved Solids (TDS), and turbidity are evaluated, as these can be significantly affected by battery waste [17]. An environmental impact index is also calculated, incorporating data on emissions and hazardous residues produced by each waste management pathway to ensure a comprehensive assessment of ecological risk. Data on these pollution parameters were obtained from prior research and direct field monitoring. The linear programming model integrates this data using weighted environmental impact scores for each parameter, ensuring that the waste is distributed in a way that minimizes ecological harm while considering the limitations of each treatment option.

**Table 1.** Pollution parameter measurement results according Gov. Reg. No. 22/2021**.**

| Parameter | Quality Standard | Recyling Side | Disposal Side | Storage Side | Remarks |
|---|---|---|---|---|---|
| pH | 6 - 9 | 7.2 | 5.8 | 6.9 | Disposal is slighty acidic |
| TDS (mg/L) | < 500 | 320 | 680 | 450 | Disposal exceeds quality standard |
| Turbidity (NTU) | < 50 | 20 | 70 | 35 | Disposal exceeds quality standard |
| Ni (mg/L) | < 0.1 | 0.05 | 0.15 | 0.08 | Disposal exceeds quality standard |
| Pb (mg/L) | < 0.05 | 0.02 | 0.07 | 0.03 | Disposal exceeds quality standard |
| Cd (mg/L) | < 0.01 | 0.005 | 0.02 | 0.008 | Disposal exceeds quality standard |

The Table 1 above presents the results of pollution parameter measurements at the Skywalker drone battery waste management site. Based on the data and accompanying graph, it is evident that the safe disposal pathway exceeds the environmental quality standards outlined in Government Regulation No. 22 of 2021 [18]. This suggests a significant risk of environmental pollution, particularly from heavy metals such as Ni, Pb, and Cd, which are toxic and potentially carcinogenic [19]. In contrast, the recycling and temporary storage pathways are safer, thanks to better processing and containment measures, which keep pollution levels within acceptable limits.

The use of linear programming enables optimal waste allocation by prioritizing pathways with the lowest environmental impact. This approach aligns with recommended best practices for battery waste management, which emphasize recycling to reduce pollution and recover valuable materials [20]. To effectively manage Skywalker drone battery waste, recycling and temporary storage should be prioritized, while reliance on landfilling must be minimized due to its higher pollution potential. Robust regulations and oversight are essential to ensure environmentally sound and sustainable battery waste management.

### 3.3. *Cost analysis of battery waste management scenarios.*

Managing Skywalker drone battery waste plays a vital role in protecting environmental sustainability and public health. These batteries contain heavy metals and other hazardous substances that require specialized treatment. This study applies a linear programming model to determine the most cost-effective and environmentally friendly waste management pathways. Cost evaluations were conducted in the context of Jakarta, which serves as a hub for waste management and technology operations. The linear programming model allocates battery waste to three main pathways: recycling, safe disposal, and temporary storage. The objective is to minimize total management costs while considering the capacity and operational constraints of each option. Cost data were sourced from official government reports and studies on B3 waste management in Jakarta [21].

Battery waste management costs cover several key components. These include waste collection and separation, which involve gathering used batteries and sorting them from other waste streams. Transportation and temporary storage costs cover logistics and the safe containment of waste prior to treatment. Recycling costs include expenses for chemical processing, energy use, and labor required to recover valuable materials. Safe disposal costs are incurred when waste that cannot be recycled must be treated and contained in accordance with environmental regulations. Lastly, administrative and supervision costs account for the oversight and coordination required to ensure compliance, efficiency, and accountability across all stages of the waste management process. Together, these components represent the full financial framework needed for sustainable battery waste management (Figure 2).

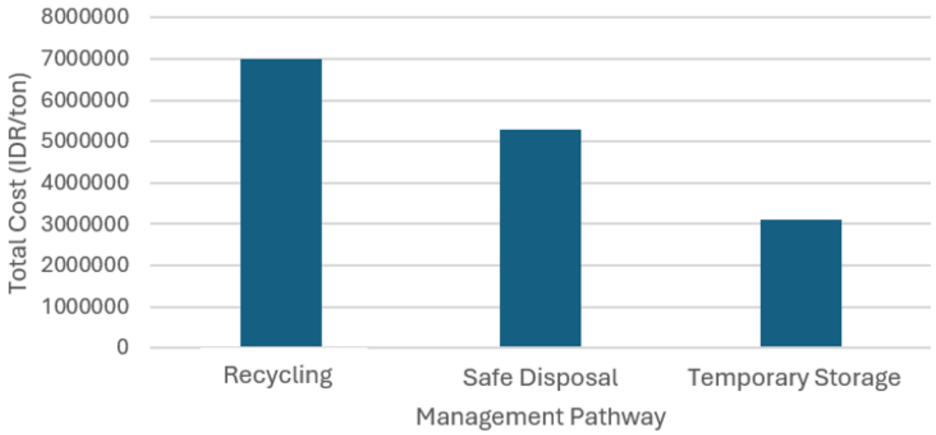

**Figure 1**. Battery waste management cost per line.

The cost evaluation reveals that the recycling pathway incurs the highest expense due to the complexity of chemical processing, energy requirements, and the need for specialized equipment and materials. Despite the high operational cost, recycling offers significant long-term economic benefits by recovering valuable metals such as nickel and cobalt. This reduces dependency on primary raw materials and lowers environmental impacts associated with mining and raw material extraction [22].

Safe disposal falls in the moderate cost range but carries a higher environmental risk if not properly managed. Temporary storage is the least expensive option; however, it is not a viable long-term solution, as it only delays the environmental risks and still requires further treatment. The application of linear programming in this study allows for an optimized allocation of battery waste, minimizing both total cost and environmental burden while respecting capacity and technical limitations of each pathway. This optimization plays a key role in supporting sustainable waste management policies, particularly for high-risk waste streams like lithium batteries in urban centers. The analysis highlights that although recycling involves higher upfront costs, its long-term environmental and economic returns make it the most sustainable option. Safe disposal and temporary storage may serve as interim or complementary approaches but should be limited to minimize contamination risks. Therefore, the development of local recycling facilities and the introduction of economic incentives for environmentally responsible practices are essential steps toward achieving a circular economy in the battery sector [23]

To strengthen the findings, the study also compares pre- and post-optimization scenarios, evaluating both environmental impact and management costs. Initially, battery waste allocation was unstructured, heavily relying on safe disposal and temporary storage. This inefficient distribution not only led to higher environmental risks but also lacked cost-effectiveness. The optimized model provides a structured, data-driven solution to guide waste distribution toward more sustainable outcomes (Table 2).

**Table 2.** Scenario results before optimization.

| Management Pathway | Waste Proportion (%) | Environmental Impact (Index) | Management Cost (IDR/ton) |
|---|---|---|---|
| Recycling | 20 | 45 | 7.000.000 |
| Safe Disposal | 50 | 70 | 5.300.000 |
| Temporary Storage | 30 | 40 | 3.100.000 |

The environmental impact is particularly high for the safe disposal pathway, which generates emissions and hazardous residues that exceed permissible safety limits. Although disposal and temporary storage incur relatively lower management costs, they pose significantly higher environmental risks [24]. By applying the linear programming approach, the allocation of battery waste is optimized to strike a balance between minimizing environmental impact and reducing overall management costs. The resulting optimized distribution of waste across recycling, safe disposal, and temporary storage is shownd in Table 3.

**Table 3.** Scenario results after optimization.

| Management Pathway | Waste Proportion (%) | Environmental Impact (Index) | Management Cost (IDR/ton) |
|---|---|---|---|
| Recycling | 65 | 30 | 7.000.000 |
| Safe Disposal | 25 | 50 | 5.300.000 |
| Temporary Storage | 10 | 20 | 3.100.000 |

The optimization process increases the allocation to recycling pathways, which offer the lowest environmental impact despite having the highest management costs. In contrast, disposal and temporary storage are minimized to reduce the potential for environmental contamination. This approach aligns with the principles of a circular economy and sustainable waste management practices [25]. The Table 4 illustrates a notable reduction in the environmental impact index following optimization and Table 5 shows the total cost of management increases slightly due to increased allocation to more expensive recycling, but provides long-term benefits.

**Table 4.** Environmental impact comparison results.

| Management Pathway | Environmental Impact (Before) | Environmental Impact (After) |
|---|---|---|
| Recycling | 45 | 30 |
| Safe Disposal | 70 | 50 |
| Temporary Storage | 40 | 20 |

**Table 5.** Comparison of management costs.

| Management Pathway | Cost Before (IDR/ton) | Cost After (IDR/ton) |
|---|---|---|
| Recycling | 7.000.000 | 7.000.000 |
| Safe Disposal | 5.300.000 | 5.300.000 |
| Temporary Storage | 3.100.000 | 3.100.000 |

The total management cost increased by approximately 10–15% compared to the pre-optimization scenario, but this was accompanied by a substantial reduction in environmental impact. Based on the data analysis, the optimization of Skywalker drone battery waste management in Jakarta successfully shifted waste allocation toward the more environmentally friendly recycling pathway. Although the management cost rose slightly, the long-term environmental and sustainability benefits far outweigh the added expenses. The reduced reliance on landfill and temporary storage pathways lowers the risk of pollution and aligns with sustainable B3 (hazardous and toxic waste) management policies [26].

### *3.4. Profit optimization and fuzzy linear programming models (2024–2025).*

The management of lithium battery waste from drones represents a critical environmental and economic challenge. The Skywalker Drone Company has been working to optimize battery waste handling for the years 2024 and 2025, aiming to balance profitability and environmental responsibility. This analysis applies the Linear Programming (LP) method to determine the optimal allocation strategy. Two models are developed: a standard (non-fuzzy) model that operates under strict resource constraints, and a flexible (fuzzy) model that permits a 10% tolerance in raw material inputs.

The drone industry permits the inclusion of up to 10% additional battery waste per unit to accommodate operational flexibility. Each unit of lithium battery waste management is projected to yield a profit of IDR 300 million in 2024 and IDR 450 million in 2025. Even a slight increase in waste processing capacity can lead to substantial gains in profit. The initial data on battery production requirements and allowable tolerances are compiled from prior studies, scientific publications, and projections from the Ministry of Environment and Forestry (KLHK) and waste management agencies for 2024–2025, as summarized in the Table 6.

**Table 6.** Battery production requirements and tolerances.

| Raw Material | Unit Rate | | Production Battery Requirements | |
|---|---|---|---|---|
| | 2024 | 2025 | Total Material | Tolerance |
| 3 cell | 20 | 15 | 100 | 10%*100 = 10 (P1) |
| 4 cell | 3 | 2,5 | 40 | 10%*40 = 4 (P2) |
| 5 cell | 5 | 8 | 30 | 10%*30 = 3 (P3) |
| 6 cell | 1,5 | 2 | 8 | 10%*8 = 0,8 (P4) |

In the mathematical model developed for this study, the primary decision variables are defined as the number of waste management production units planned for two consecutive years—2024 and 2025—represented by $x_1$ and $x_2$, respectively. To simplify analysis and calculations, the profit per unit has been expressed using a scaled system. Specifically, the profit for each unit in 2024 ($x_1$) is scaled to 10, equivalent to an actual profit of 300 million rupiah, while for 2025 ($x_2$), it is scaled to 15, representing 450 million rupiah. The overall scaling factor used in the model is 30 million rupiah, meaning each unit in the objective function corresponds to that amount in actual profit. This scaling allows the model to remain computationally manageable while maintaining a direct connection to real-world financial values for practical planning and decision-making.

In the non-fuzzy model, all input parameters such as production requirements, resource quantities, and tolerances, are treated as fixed values. The objective of this optimization is to maximize profit by producing two battery types: 3-cell ($x_1$) and 4-cell ($x_2$), within the constraints of available raw materials and permitted tolerances. The linear programming model is designed to maximize total profit ($Z$) from battery waste management operations over 2024 and 2025. The objective function is defined as:

$$Maximize\ Z = 10x_1 + 15x_2$$

Here, $x_1$ and $x_2$ are the number of units produced in 2024 and 2025, respectively, and 10 and 15 are their respective scaled profit coefficients. This formulation reflects the company's goal of maximizing profitability through effective resource allocation across two production years.

The model includes critical constraints representing the limited availability of different battery cell types. These are rigid (non-fuzzy) limits, meaning the model does not allow exceeding the available raw material quantities. The constraints are as follows: 3-cell batteries: $20x_1 + 15x_2 \leq 100$, 4-cell batteries: $3x_1 + 2.5x_2 \leq 40$, 5-cell batteries: $5x_1 + 8x_2 \leq 30$, 6-cell batteries: $1.5x_1 + 2x_2 \leq 8$. These ensure that the production plan remains realistic and does not exceed the available stock of each battery cell type. Non-negativity constraints ($x_1 \geq 0$, $x_2 \geq 0$) are also enforced, as negative production values are infeasible. This linear programming approach follows standard optimization practices in production planning [27, 28], effectively balancing profitability with material constraints.

In the fuzzy model, certain parameters are considered uncertain and are modeled using fuzzy set theory. In this context, uncertainties in raw material availability are incorporated through a membership function, and constraints are made more flexible. A fuzzy linear programming approach introduces a satisfaction level variable $\lambda$ (lambda), ranging from 0 to 1, which represents the degree to which constraints are satisfied. The objective function in this fuzzy model becomes:

$$Maximize\ Z = \lambda$$

Here, $\lambda$ reflects the overall satisfaction level of meeting all fuzzy constraints. A value of $\lambda$ close to 1 indicates high feasibility under the given conditions. This approach allows for more flexibility in managing raw material inputs, which is more aligned with real-world uncertainties in waste collection and sorting processes.

In this case, the model permits a 10% increase in the availability of raw materials over their base limits. The revised constraints become: 3-cell batteries: $20x_1 + 15x_2 \leq 110$, 4-cell batteries: $3x_1 + 2.5x_2 \leq 44$, 5-cell batteries: $5x_1 + 8x_2 \leq 33$, and 6-cell batteries: $1.5x_1 + 2x_2 \leq 8.8$. These adjustments allow the model to better reflect fluctuations in supply without invalidating the solution. The $\lambda$ parameter is embedded in each constraint, ensuring that the model adapts to different levels of resource availability. This fuzzy linear programming approach is particularly relevant to waste battery management, where the exact quantity of recyclable or usable components can vary due to collection rates, degradation, and processing efficiencies [29]. By integrating uncertainty into the model, the approach provides solutions that are both robust and applicable in real operational contexts. Non-negativity constraints still apply, as production values must remain non-negative. Overall, the fuzzy model enhances traditional linear programming by allowing greater flexibility in uncertain environments, supporting more adaptive and sustainable decision-making in lithium battery waste management (Table 7 and Table 8).

**Table 7.** Calculation using solver for non-fuzzy models.

| Parameter | 3 Cell | 4 Cell | 5 ell | 6 Cell |
|---|---|---|---|---|
| Demand 2024 ($x_1$) | 20 | 3 | 5 | 1.5 |
| Demand 2025 ($x_2$) | 15 | 2.5 | 8 | 2 |
| Total Material | 100 | 40 | 30 | 8 |
| Tolerance (10%) | 10 | 4 | 3 | 0.8 |
| Demand Formula Result | 85.25 | 13.475 | 33 | 8.8 |

**Table 8.** Solver results.

| Parameter | Value |
|---|---|
| $X_1$ (Production 2024) | 2.2 |
| $X_2$ (Production 2025) | 2.75 |
| Objective Function | - |
| Profit per unit $x_1$ | 10 |
| Profit per unit $x_2$ | 15 |
| Z Value (Total Profit) | 63.25 |

The optimal solution derived from the fuzzy linear programming model effectively utilized the flexibility provided by the tolerance limits to maximize the company's profit in waste battery management for 2024 and 2025. The calculated production levels were 2.2 units for 2024 ($x_1$) and 2.75 units for 2025 ($x_2$), reflecting a well-balanced strategy between resource availability and profit generation. An analysis of material consumption showed that the usage of 3-cell and 4-cell batteries remained well within their original constraints, 85.25 units were used against a limit of 100, and 13.475 units against a limit of 40, respectively. Meanwhile, the consumption of 5-cell and 6-cell batteries slightly exceeded the initial rigid limits but stayed within the 10% tolerance range. Specifically, 33 units of 5-cell batteries were consumed (original limit of 30, extended to 33), and 8.8 units of 6-cell batteries were used (original limit of 8, extended to 8.8).

These results illustrated how the fuzzy model's flexible constraints accommodated real-world variability in raw material availability. This allowed the company to slightly increase production without violating feasibility, a key advantage over rigid models that would have strictly restricted production to the original limits [30, 31]. The total profit, based on scaled units, was calculated as $Z = 10(2.2) + 15(2.75) = 63.25$ units. When converted into actual currency, this equaled a total profit of IDR 1,897,500,000 (63.25 × 30,000,000), demonstrating the financial benefit of incorporating tolerance margins into production planning. This approach supported the findings of Chen et al. (2019) and other researchers who emphasized the advantages of fuzzy optimization in managing uncertainties in resource supply and production planning. By introducing controlled flexibility, companies could better handle fluctuations in material availability while optimizing profit and promoting sustainable operations. Overall, the analysis showed that by utilizing the allowed addition of raw materials especially for 5-cell and 6-cell batteries, the company achieved a maximum profit of IDR 1.8975 billion. This solution represented the optimal target if the company successfully realized the additional resource allowance up to the 10% tolerance. Optimization with Partial Tolerance is shown in Table 9 and Table 10.

**Table 9.** Calculations using solvers for fuzzy models**.**

| Variable | x1 | x2 | λ | s1 | s2 | s3 | s4 | s5 | Solution |
|---|---|---|---|---|---|---|---|---|---|
| z | -10 | -15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $s_1$ | 20 | 15 | -10 | 1 | 0 | 0 | 0 | 0 | 100 |
| $s_2$ | 3 | 2.5 | -4 | 0 | 1 | 0 | 0 | 0 | 40 |
| $s_3$ | 5 | 8 | -3 | 0 | 0 | 1 | 0 | 0 | 30 |
| $s_4$ | 1.5 | 2 | -0.8 | 0 | 0 | 0 | 1 | 0 | 8 |

**Table 10.** Solver results.

| Variable | Initial Value | Objective Function Value | Variable |
|---|---|---|---|
| $x_1$ | 2.1 | 60.375 | z |
| $x_2$ | 2.625 | 76.375 | $s_1$ |
| λ | 0.5 | 10.8625 | $s_2$ |
| | | 30 | $s_3$ |
| | | 8 | $s_4$ |

The second solution generated by the fuzzy solver presented a slightly different production allocation for 2024 and 2025—2.1 units for 2024 ($x_1$) and 2.625 units for 2025 ($x_2$). This approach utilized only part of the available tolerance in raw material constraints, reflecting a more conservative yet still flexible strategy in resource planning. The material consumption analysis showed that 3-cell and 4-cell battery usage remained comfortably within both the original limits and their 10% tolerance margins, with consumption values of 81.375 and 11.325 units, respectively—well below their upper thresholds of 110 and 44 units. For the 5-cell and 6-cell batteries, consumption slightly exceeded the rigid original limits but only partially used the allowed tolerance. Specifically, the 5-cell battery consumption reached 31.5 units—1.5 units above the original limit of 30, representing just 50% of the 10% tolerance margin (maximum allowed: 33 units). Similarly, 6-cell battery usage totaled 8.4 units—0.4 units above the strict limit of 8, or 50% of the allowed tolerance up to 8.8 units.

This partial utilization of tolerance indicated a deliberate strategy to balance production levels while cautiously managing resource flexibility. Such an approach likely aimed to minimize potential risks associated with overextending supply or uncertainty in raw material availability, offering greater control over operational stability. The resulting profit, calculated using scaled profit values, was $Z = 10(2.1) + 15(2.625) = 60.375$ units. When converted to actual currency, this yielded a total profit of IDR 1,811,250,000 (60.375 × 30,000,000). While this was slightly lower than the profit in the first solution, it represented a conscious trade-off that prioritized measured resource use and risk mitigation.

These findings supported previous research by [29, 30], highlighting the strength of fuzzy optimization models in managing uncertainty through adjustable tolerance levels. The ability to apply tolerance selectively gave decision-makers flexibility to tailor production plans according to risk preferences and supply chain dynamics. This scenario demonstrated how the company could choose or be constrained to utilize only 50% of its available flexibility. Despite the lower profit of IDR 1.81125 billion compared to the fully optimized case, this outcome was still more favorable than what would have resulted from strictly applying rigid (non-fuzzy) constraints. Under a purely non-fuzzy model, production would have been capped at the original limits (30 and 8 units), likely resulting in significantly lower profitability. Thus, this solution illustrated the practical advantage of fuzzy linear programming in navigating real-world uncertainties in waste battery management.

## 4. Conclusions

The application of a Linear Programming model using a flexible, fuzzy approach clearly demonstrated that introducing tolerance in raw material availability significantly enhanced profitability. Even a modest 10% increase in the supply of critical raw materials led directly to higher revenue, underscoring the strategic value of flexibility in resource management. The optimal solution identified in this analysis recommended producing 2.2 units in 2024 and 2.75 units in 2025, resulting in a maximum profit of IDR 1.8975 billion. This outcome fully utilized the 10% tolerance capacity for 5-cell and 6-cell battery raw materials, both identified as the primary constraints limiting production and profit. These two battery types were the critical bottlenecks in the system, and addressing their limited supply became key to unlocking higher output. To capitalize on this insight, the company should prioritize securing additional and consistent sources of 5-cell and 6-cell battery waste. Strengthening supply chain flexibility for these materials will be essential not only for maintaining current profit margins but also for scaling future production capacity. Beyond the economic gains, this optimization strategy also supported a more efficient and structured approach to battery waste management. By maximizing the productive use of waste materials, the model promoted practices aligned with environmental sustainability encouraging resource conservation, reducing landfill dependency, and advancing circular economy goals

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## Author Contribution

The contributors to this work include Cynthia Rahmawati focusing on ecotoxicity, waste, cycle, degradation, and mitigation; Endah Yuniarti working on energy, aerodynamics, footprint, emissions, and kinetics; Munnik Haryanti covering electronics, efficiency, impedance, reclamation, and regulation; Bekti Yulianti specializing in efficiency, circuit, autonomy, and cycle; Syarifah Fairuza addressing propulsion, weight, manufacturing, and residue; and Muhammad Yazid Ashari, contributing to simulation, data, characterization, modeling, and preservation.

## Competing Interest

All authors declare that the research presented in the manuscript titled *"Analysis of the Impact of Skywalker Drone Battery Waste Management on the Environment Using Linear Programming Method"* was carried out without any commercial or financial relationships that could be seen as a potential conflict of interest. The study received internal funding from Universitas Dirgantara Marsekal Suryadarma (UNSURYA) through its Lembaga Penelitian dan Pengabdian Masyarakat (LPPM). The authors affirm that this funding source had no influence on the study's design, execution, analysis, or interpretation, and did not affect the decision to submit the manuscript for publication. The views expressed are solely those of the authors.

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