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## BREAK-EVEN CONVERSION THRESHOLDS FOR MINING WASTE REVERSE SUPPLY CHAINS

**Abstract.** Reverse supply chains (RSCs) have been increasingly promoted as a mechanism for improving resource efficiency and reducing environmental impacts in mining industries. However, in emerging economies such as Kazakhstan, the economic feasibility of mining waste recycling remains uncertain due to long transportation distances, high operational costs, and limited processing infrastructure. While previous studies have demonstrated the potential of optimization-based reverse logistics models, conversion efficiency is commonly treated as an assumed or fixed parameter rather than a critical feasibility condition. This limits the practical applicability of existing models for decision-makers.

This study addresses this gap by conducting a threshold (break-even) analysis to identify the minimum conversion efficiency required for reverse supply chain operations to achieve economic viability in Kazakhstan's mining sector. Building upon an established reverse supply chain cost structure, the proposed approach evaluates system profitability across a range of conversion efficiency levels under alternative logistics scenarios. The analysis focuses on the relationship between conversion efficiency and aggregated cost drivers, including transportation, processing, and fixed operational costs.

The results demonstrate that reverse supply chain feasibility is highly sensitive to conversion efficiency and that profitability can only be achieved once a clearly defined conversion threshold is exceeded. Below this threshold, improvements in logistics efficiency alone are insufficient to offset total system costs. The findings highlight conversion efficiency as a dominant strategic parameter in early-stage reverse supply chain planning for mining waste recycling.

By explicitly defining conversion efficiency thresholds, this study provides a practical decision-support tool for policymakers and industry stakeholders. The results contribute to the development of economically grounded reverse supply chain strategies and support the transition toward sustainable and circular mining practices in Kazakhstan.

**Key words:** reverse supply chain, conversion efficiency, break-even analysis, mining waste recycling, economic feasibility

### Introduction.

The mining industry is a highly resource-intensive sector that generates large volumes of waste during extraction and processing. In many mining regions, including Kazakhstan, large-scale accumulation of tailings and other mining residues poses long-term environmental and economic challenges. As sustainability and circular economy agendas expand, the recovery of valuable materials from mining waste has attracted growing attention from both researchers and policymakers [1].

RSCs, which encompass the collection, transportation, processing, and reuse of waste materials, are widely recognized as a key mechanism for improving resource efficiency and reducing environmental impacts in industrial systems [2,3]. In the mining context, reverse logistics offers an opportunity to transform waste streams into secondary resources while reducing reliance on landfilling and long-term storage of tailings [4]. However, the practical implementation of reverse supply chains for mining waste remains limited, particularly in geographically large countries characterized by long transport distances and dispersed waste sources.

Economic feasibility depends on both logistics' performance and processing efficiency. Conversion efficiency, defined as the share of input waste successfully transformed into marketable output, directly affects both revenue generation and operating costs. Despite its importance, conversion efficiency is frequently treated as a fixed or assumed parameter in reverse supply chain models rather than as a critical decision variable [5]. Figure 1 illustrates the general structure of a mining reverse supply chain, highlighting the role of conversion efficiency (Conv) in transforming mining waste into marketable output.

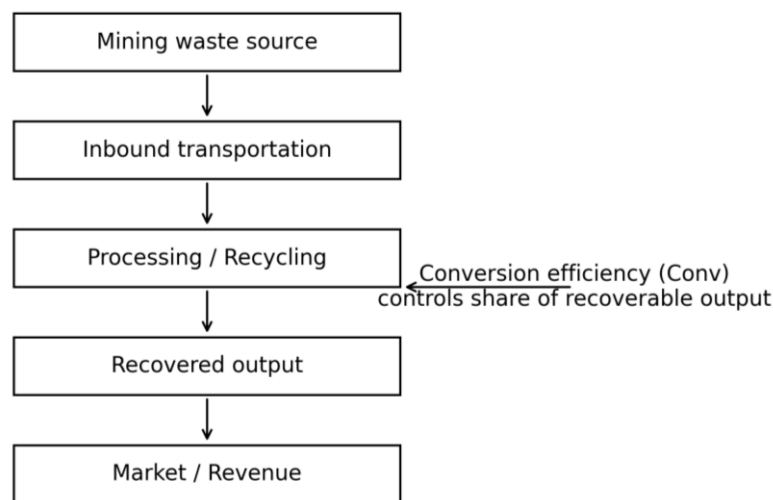


Figure 1 – Conceptual structure of a mining reverse supply chain

In previous work by the authors, a reverse supply chain optimization framework for mining waste was proposed, where conversion efficiency was explicitly introduced as a parameter influencing profitability [5]. The results demonstrated that increasing conversion efficiency significantly improves economic outcomes and that system profitability approaches break-even at higher conversion levels. However, the analysis did not explicitly identify the minimum conversion efficiency required to achieve economic viability, leaving an important managerial question unanswered.

From a practical perspective, decision-makers require clear feasibility conditions to evaluate whether investment in recycling infrastructure is justified under given market and logistical constraints. In particular, identifying a break-even conversion threshold would allow stakeholders to assess whether existing or planned processing technologies are capable of supporting economically viable reverse supply chain operations. Without such thresholds, reverse supply chain models remain difficult to translate into actionable policy or investment decisions.

Therefore, this study addresses the following research question: What is the minimum conversion efficiency (Conv\*) required for a reverse supply chain to reach break-even profitability in the context of mining waste recycling? To answer this question, a threshold-based break-even analysis is conducted using a simplified cost structure and scenario-based pricing assumptions. By explicitly deriving conversion efficiency thresholds, the study contributes to bridging the gap

between conceptual reverse supply chain models and practical feasibility assessment for mining waste recycling initiatives in Kazakhstan.

The scientific novelty of the study consists of the following contributions. First, the paper introduces an explicit closed-form derivation of the minimum conversion efficiency threshold (Conv\*) required for break-even profitability in mining waste reverse supply chains. Second, unlike existing reverse logistics optimization studies that assume recovery efficiency as an exogenous parameter, this research treats conversion efficiency as a feasibility boundary condition. Third, the study operationalizes threshold analysis as a decision-support instrument tailored to emerging economies characterized by long transport distances.

#### **Literature review.**

Previous studies on reverse supply chains in mining and heavy industries have primarily focused on logistics network design, facility location, and transportation cost minimization [6-8]. Optimization-based approaches have been applied to determine the most cost-efficient placement of collection or processing centers and to reduce total transport distance [9]. While these studies provide valuable insights into spatial and logistical aspects of reverse supply chain design, they often assume that recycling or recovery processes are technically and economically feasible once logistics are optimized.

Techno-economic studies show that profitability depends on both logistics costs and process performance [10]. Therefore, a spatially optimal network may remain unprofitable when recovery performance is insufficient to offset total costs.

Recent studies have evaluated mining waste recycling using entropy-based processability metrics combined with economic revenue estimation [11]. While such approaches quantify the technical recoverability and economic potential of waste streams, they do not explicitly derive analytical feasibility thresholds that determine the minimum technical efficiency required for break-even conditions.

More broadly, existing techno-economic assessments typically evaluate project profitability under assumed recovery rates and cost structures, often through scenario or sensitivity analysis. However, they rarely derive analytical feasibility boundaries identifying the minimum technical performance required for economic viability.

A systematic examination of existing literature reveals three recurring limitations. First, recovery or conversion efficiency is predominantly treated as an exogenous input parameter rather than as a feasibility boundary condition. Second, economic viability is assessed through scenario or sensitivity analysis without formal derivation of minimum technical performance requirements. Third, profitability analysis is typically conducted under fixed throughput and cost assumptions, limiting its ability to identify structural feasibility constraints in transport-intensive mining systems.

In contrast, the proposed approach explicitly formulates and solves for the break-even conversion threshold (Conv\*), thereby transforming technical efficiency from an assumed parameter into a strategic feasibility boundary condition.

The transition toward circular economy principles has increasingly shaped international research on mining waste recycling. Circular economy frameworks promote the reintegration of secondary materials into production systems, the reduction of primary resource extraction, and the extension of material life cycles. In the mining sector, these objectives are closely linked to the concept of industrial symbiosis, where waste generated by one process is used as input for another industrial activity.

International studies indicate that the implementation of circular economy strategies in mining depends not only on technological solutions but also on economic feasibility. Industrial symbiosis initiatives require stable material flows, adequate recovery efficiency, and cost structures that allow secondary materials to remain competitive in the market. However, although the literature widely discusses environmental benefits and systemic integration of mining waste within circular networks, the economic feasibility of such systems is often assessed in qualitative

terms. Quantitative conditions that link technical recovery performance to break-even profitability are rarely formalized.

In this context, identifying a minimum conversion efficiency threshold becomes essential for translating circular economy strategies into practical decision-making tools. By explicitly defining the technical performance level required to achieve economic viability, the present study contributes to operationalizing circular economy and industrial symbiosis principles in transport-intensive mining systems.

### Materials and methods.

To perform the break-even analysis, a simplified reverse supply chain model was parameterized using a case study-based configuration representative of mining waste transportation and pilot-scale processing conditions in Kazakhstan. The parameter set reflects technical constraints of the experimental equipment, operational assumptions, and logistics characteristics typical for long-distance waste transport scenarios.

The model inputs were derived from a combination of equipment specifications, project-level operational data, and engineering assumptions required for early-stage feasibility assessment. Due to the exploratory nature of the study and the absence of large-scale industrial implementations, several parameters were defined based on realistic operational limits and commonly accepted practice in logistics and processing system modeling.

Table 1 summarizes the key parameters used in the break-even analysis, including throughput constraints, transportation characteristics, operating conditions, and cost components.

Table 1 – Input parameters and assumptions

Parameter	Description	Value	Unit	Source / Assumption
$Q_{day}$	Processing capacity of equipment	10	t/day	Equipment specification
$D$	Operating days per year	330	days/year	Assumed (maintenance included)
$x$	Annual waste throughput	3300	t/year	$x = Q_{day} * D$
$C_{ap}$	Truck capacity	25	t/trip	Non-hazardous cargo
$d$	Distance to processing facility (Balkhash–Almaty)	638	km	Case study
$C_{trip}$	Transport cost per trip	364.64	USD/trip	285 KZT/km, converted
$N$	Number of trips per year	132	trips/year	$N = x/C_{ap}$
$C_{tin}$	Annual inbound transport cost	48,133	USD/year	$N * C_{trip}$
$K_{el}$	Total installed power	3.42	kW	Equipment data
$h$	Daily operating hours	12	h/day	Assumed
$C_{op}$	Annual electricity cost	543	USD/year	kWh
$C_{fix}$	Fixed annual cost	608	USD/year	Project data
$p$	Selling price of recovered output	20, 30, 50	USD/t	Scenario analysis

To evaluate the economic feasibility of reverse supply chain operations, a break-even analysis based on conversion efficiency was conducted. The analysis focuses on identifying the minimum conversion efficiency required for the reverse supply chain to achieve zero profit, which is defined as the break-even point.

To ensure analytical transparency and to focus on the impact of conversion efficiency on economic feasibility, several simplifying assumptions were adopted in the proposed break-even model.

First, the reverse supply chain configuration considers a single waste source represented by one tailings dam supplying the processing facility. This assumption reflects the pilot-scale nature of the analyzed system and allows isolation of conversion efficiency effects without introducing spatial aggregation complexity.

Second, outbound transportation cost  $C_{out}$  was set to zero. This assumption is justified by the fact that recovered output is assumed to be utilized or sold locally, or that outbound logistics costs are embedded in the market price of the recovered product.

Third, landfill disposal cost  $C_{land}$  was not included in the cost structure. This reflects a scenario in which residual waste is either temporarily stored on-site or disposed of without additional monetary cost, allowing the analysis to focus on primary economic drivers under conservative assumptions.

These assumptions result in a simplified yet representative cost structure suitable for identifying break-even conversion efficiency thresholds in early-stage feasibility assessment.

The annual profit of the reverse supply chain system is expressed as the difference between total revenue from recycled products and aggregated system costs. Profit is formulated as a function of conversion efficiency, as shown in Equation (1).

$$R(conv) = p * x * Conv - [C_{in} + C_{fix} + C_{op} * Conv + C_{out} * Conv + C_{land} * (1 - Conv)] \quad (1)$$

In this formulation,  $p$  denotes the unit selling price of recycled output (USD/ton),  $x$  represents the annual amount of waste processed (tons/year), and  $Conv$  is the conversion efficiency of the recycling process. The cost structure includes inbound transportation cost ( $C_{in}$ ), fixed operational cost ( $C_{fix}$ ), variable processing cost ( $C_{op}$ ), outbound transportation cost ( $C_{out}$ ), and landfill disposal cost for the unrecovered waste fraction ( $C_{land}$ ). Costs that are directly proportional to the recovered output are scaled by conversion efficiency, while landfill costs are applied to the non-recovered fraction.

The break-even condition is defined as the point at which total profit equals zero, as shown in Equation (2).

$$R(Conv) = 0 \quad (2)$$

Solving the profit function under this condition yields the minimum conversion efficiency threshold  $Conv$ , presented in Equation (3). This threshold represents the critical value above which reverse supply chain operations become economically viable.

$$Conv^* = \frac{C_{in} + C_{fix} + C_{land}}{p * x - (C_{op} + C_{out}) + C_{land}} \quad (3)$$

The proposed formulation allows direct estimation of feasibility boundaries under fixed throughput conditions and enables transparent evaluation of how cost structure and conversion efficiency jointly determine system profitability.

### Results and discussion.

The break-even conversion efficiency decreases nonlinearly with increasing unit selling price of the recovered output. As shown in Table 2, under Scenario 1 (20 USD/t), the system requires a conversion efficiency of at least 0.745 to reach economic feasibility. This indicates that nearly three quarters of the incoming mining waste must be successfully converted into marketable output to offset transportation and fixed operating costs.

When the unit selling price increases to 30 USD/t (Scenario 2), the break-even conversion threshold decreases to 0.495, suggesting that moderate technical performance is sufficient to achieve zero profit. Under the most favorable pricing scenario (50 USD/t), the required conversion

efficiency further decreases to 0.296, indicating that the system becomes economically viable even at relatively low recovery levels.

Table 2 - Break-even conversion efficiency thresholds under alternative price scenarios

Scenario	Unit selling price (S) (USD/t)	Conv*
Scenario 1	20	0.745
Scenario 2	30	0.495
Scenario 3	50	0.296

The results highlight the strong sensitivity of reverse supply chain feasibility to both market price and conversion efficiency. While improvements in conversion efficiency directly enhance revenue generation, higher output prices significantly relax the technical performance requirements. This confirms that conversion efficiency represents a critical feasibility driver in mining reverse supply chains, particularly under long-distance transportation conditions.

Figure 2 illustrates the nonlinear decrease in the required conversion efficiency with increasing market price of recovered output.

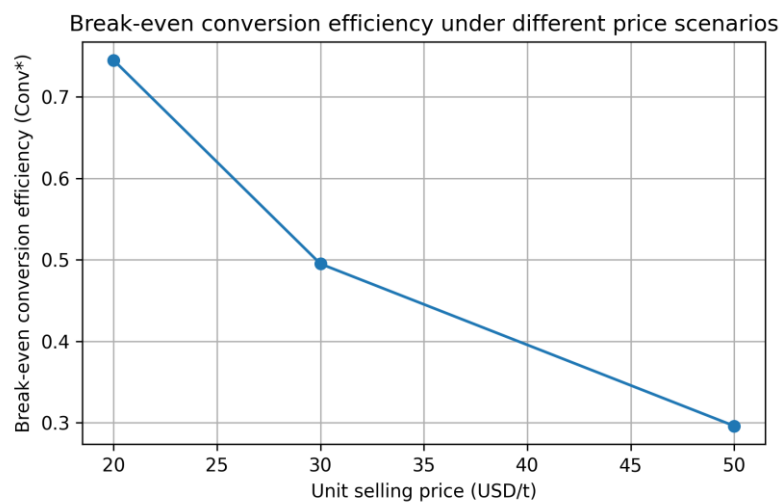


Figure 2 - Break-even conversion efficiency as a function of unit selling price

The steep decline in the conversion threshold at lower price levels indicates that economic feasibility is highly sensitive to market conditions when recovery rates are limited. As the unit selling price increases, the marginal effect of price growth on feasibility decreases, suggesting diminishing returns in relaxing technical performance requirements at higher price levels.

The break-even analysis revealed that conversion efficiency is the dominant determinant of economic feasibility in the analyzed reverse supply chain configuration. Under baseline logistics conditions, characterized by long-distance inbound transportation from Balkhash to the processing facility near Almaty, inbound transport costs constituted the largest share of annual expenses.

Across scenarios, feasibility is driven primarily by the interaction between selling price and conversion efficiency. Higher prices relax the technical performance requirement, whereas cost reductions have a comparatively smaller effect under long-distance logistics.

The most favorable scenario, corresponding to a selling price of 50 USD/t, resulted in a break-even threshold of 0.296. In this case, even moderate conversion efficiency levels are sufficient to generate non-negative profit, highlighting the strong sensitivity of system feasibility to market price assumptions. Across all scenarios, reductions in operating cost had a limited effect compared to changes in conversion efficiency, confirming that technical recovery performance plays a more critical role than marginal logistics or energy cost adjustments under long-distance transport conditions.

These findings demonstrate that reverse supply chain implementation for mining waste recycling in Kazakhstan is feasible only above clearly defined conversion efficiency thresholds.

Below these thresholds, improvements in logistics efficiency alone are insufficient to achieve profitability. From a practical perspective, the results emphasize the importance of prioritizing processing technology development and recovery rate optimization during early-stage reverse supply chain planning. For policymakers and industry stakeholders, the identified thresholds provide a transparent decision-support metric for evaluating investment readiness and technological feasibility in emerging circular mining initiatives.

#### *Risk Considerations*

Although the proposed threshold model provides a deterministic estimation of the minimum conversion efficiency required for economic viability, real-world implementation of mining reverse supply chains is subject to several categories of risk.

**Technological risks.** Conversion efficiency may vary due to heterogeneity of tailings composition, variability in mineral grades, equipment performance instability, or scale-up effects. Laboratory-level recovery rates may not fully reflect industrial operating conditions. As a result, the actual conversion efficiency achieved in practice may deviate from the calculated threshold (Conv\*), affecting profitability.

**Market risks.** Economic feasibility is sensitive to fluctuations in commodity prices and demand for recovered materials. Volatility in global metal markets may alter revenue streams and shift the break-even conversion threshold. Transport fuel price fluctuations may further influence total system costs in geographically dispersed mining regions.

**Regulatory risks.** Changes in environmental standards, waste classification policies, carbon pricing mechanisms, or subsidy schemes may significantly affect cost structures. Stricter environmental requirements could increase processing costs, while policy incentives for secondary resource use may improve economic feasibility.

Taken together, these risks indicate that the derived conversion threshold should be interpreted as a baseline feasibility condition under deterministic assumptions. Future research may extend the proposed framework by incorporating stochastic modeling or scenario-based uncertainty analysis to evaluate threshold stability under varying external conditions.

#### **Conclusion.**

This study examined conversion efficiency as a key condition for economic viability in mining waste reverse supply chains. A threshold-based break-even analysis was used to determine the minimum efficiency level required for profitability under defined cost and pricing scenarios in Kazakhstan.

The results indicate that system viability depends strongly on the interaction between selling price and technical performance. Under low-price conditions, very high conversion efficiency is required to offset transport and fixed costs. As market prices increase, the required efficiency threshold decreases, making the system more feasible.

The findings show that logistics optimization alone does not guarantee profitability, particularly in transport-intensive mining regions. Economic viability depends equally on processing performance. Therefore, conversion efficiency should be considered an early-stage feasibility indicator rather than a fixed technical assumption.

Although the analysis is based on simplified assumptions and a single-source configuration, the proposed framework provides a clear analytical tool for evaluating mining waste recycling projects. Future research may extend the model to include multiple waste sources, alternative cost structures, and uncertainty factors to support more comprehensive decision-making in circular mining systems.

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## **ПОРОГОВЫЕ ЗНАЧЕНИЯ КОЭФФИЦИЕНТА КОНВЕРСИИ ДЛЯ ОБРАТНОЙ ЦЕПИ ПОСТАВКИ ГОРНОПРОМЫШЛЕННЫХ ОТХОДОВ**

***Аннотация.** Обратная цепь поставки (ОЦП) все чаще рассматривается как эффективный механизм повышения ресурсной эффективности и снижения негативного воздействия на окружающую среду в горнодобывающей промышленности. Однако в развивающихся экономиках, таких как Казахстан, экономическая целесообразность переработки горнопромышленных отходов остается неопределенной вследствие значительных транспортных расстояний, высоких эксплуатационных затрат и ограниченной перерабатывающей инфраструктуры. Несмотря на то, что предыдущие исследования демонстрируют потенциал оптимизационных моделей обратной логистики, коэффициент конверсии, как правило, рассматривается как заданный или фиксированный параметр, а не как критическое условие экономической осуществимости. Это*

существенно ограничивает практическую применимость существующих моделей для лиц, принимающих решения.

В данной работе указанный пробел восполняется посредством проведения порогового (безубыточного) анализа, направленного на определение минимального коэффициента конверсии, необходимого для достижения экономической устойчивости операций обратной цепи поставки в горнодобывающем секторе Казахстана. На основе сформированной структуры затрат обратной цепи поставки предложенный подход позволяет оценить рентабельность системы в широком диапазоне значений коэффициента конверсии при альтернативных логистических сценариях. Анализ сосредоточен на взаимосвязи между коэффициентом конверсии и агрегированными факторами затрат, включая транспортные, перерабатывающие и фиксированные эксплуатационные расходы.

Полученные результаты показывают, что экономическая осуществимость обратной цепи поставки в высокой степени чувствительна к уровню коэффициента конверсии и что достижение прибыльности возможно лишь при превышении четко определенного порогового значения. Ниже данного порога повышение эффективности логистики само по себе не позволяет компенсировать совокупные издержки системы. Результаты исследования подчеркивают доминирующую роль коэффициента конверсии как стратегического параметра на ранних этапах планирования обратной цепи поставки для переработки горнопромышленных отходов.

Четкое определение пороговых значений коэффициента конверсии позволяет предложить практико-ориентированный инструмент поддержки принятия решений для государственных органов и представителей промышленности. Полученные выводы вносят вклад в формирование экономически обоснованных стратегий развития обратной цепи поставки и способствуют переходу к устойчивым и циркулярным практикам в горнодобывающей промышленности Казахстана.

**Ключевые слова:** обратная цепь поставки, коэффициент конверсии, анализ безубыточности, переработка горнопромышленных отходов, экономическая целесообразность

## **ТАУКЕН ҚАЛДЫҚТАРЫНА АРНАЛҒАН КЕРІ ЖЕТКІЗУ ТІЗБЕКТЕРІНДЕГІ КОНВЕРСИЯ КОЭФФИЦИЕНТІНІҢ ӨТЕЛІМДІЛІК ШЕКТІ МӘНДЕРІ**

**Аңдатпа.** Кері жеткізу тізбектері (КЖТ) таукен өнеркәсібінде ресурстарды тиімді пайдалануды арттыру және қоршаған ортаға түсетін теріс әсерді азайту тетігі ретінде барған сайын кеңінен қарастырылуда. Алайда Қазақстан сияқты дамушы экономикаларда таукен қалдықтарын қайта өңдеудің экономикалық орындылығы ұзақ тасымалдау қашықтықтары, жоғары пайдалану шығындары және өңдеу инфрақұрылымының шектеулілігі салдарынан белгісіз болып отыр. Алдыңғы зерттеулер кері логистикаға негізделген оңтайландыру модельдерінің әлеуетін көрсеткенімен, конверсия коэффициенті көбінесе экономикалық орындылықтың негізгі шарты ретінде емес, берілген немесе тұрақты параметр ретінде қарастырылады. Бұл жағдай қолданыстағы модельдердің практикалық шешім қабылдау үдерісіндегі қолданылуын шектейді.

Аталған мәселені шешу мақсатында бұл зерттеуде шекті (өтелімділік) талдау жүргізіліп, Қазақстанның тау-кен секторында кері жеткізу тізбектерінің экономикалық тиімділігіне қол жеткізу үшін қажетті ең төменгі конверсия коэффициенті анықталады. Кері жеткізу тізбегінің шығын құрылымына негізделе отырып, ұсынылған тәсіл әртүрлі логистикалық сценарийлер жағдайында конверсия коэффициентінің түрлі деңгейлері бойынша жүйенің рентабельділігін бағалауға мүмкіндік береді. Талдау тасымалдау, өңдеу және тұрақты пайдалану шығындарын қамтитын жиынтық шығын факторлары мен конверсия коэффициенті арасындағы өзара байланысты зерттеуге бағытталған.

*Зерттеу нәтижелері кері жеткізу тізбектерінің экономикалық орындылығы конверсия коэффициентіне айтарлықтай тәуелді екенін және табыстылыққа тек нақты анықталған шекті мәннен асқан жағдайда ғана қол жеткізуге болатынын көрсетеді. Аталған шектен төмен жағдайда логистикалық тиімділікті арттырудың өзі жүйенің жалпы шығындарын өтеуге жеткіліксіз. Алынған нәтижелер таукен қалдықтарын қайта өңдеуге арналған кері жеткізу тізбектерін жоспарлаудың бастапқы кезеңдерінде конверсия коэффициентінің басым стратегиялық параметр ретіндегі маңыздылығын айқындайды.*

*Конверсия коэффициентінің шекті мәндерін нақты анықтау мемлекеттік органдар мен өнеркәсіп өкілдері үшін практикалық шешім қабылдауды қолдайтын құрал ұсынады. Зерттеу нәтижелері экономикалық тұрғыдан негізделген кері жеткізу тізбегі стратегияларын дамытуға үлес қосып, Қазақстанның таукен өнеркәсібінде тұрақты және циркулярлық тәжірибелерге көшуге ықпал етеді.*

**Түйін сөздер:** кері жеткізу тізбегі, конверсия коэффициенті, өтелімділік талдау, таукен қалдықтарын қайта өңдеу, экономикалық орындылық.

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