Transport-Related Carbon Emissions of Imported Timber Supply in Kazakhstan

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In the context of Kazakhstan's strategy to achieve carbon neutrality by 2060, assessing transport-related CO_2 emissions associated with imported timber supply has become increasingly important. For Kazakhstan, this issue is particularly relevant for Kazakhstan because its woodworking industry depends heavily on imported timber transported over long distances. The objective of this study was to assess CO_2 emissions generated during the transportation of imported sawn timber to Kazakhstan, through a comparative analysis of transport-related CO_2 emissions under different logistics scenarios and a comparison of logistics scenarios. The study considers three logistics supply scenarios: rail transport, road transport, and a combined scenario (rail transport followed by a road segment). Calculations were based on a distance-oriented model using average emission factors consistent with international databases. One tonne of sawn timber is adopted as the functional unit. The results showed that rail transport provides the lowest emission level (62 kg CO_2/t), whereas road transport generated substantially higher transport-related CO_2 emissions (153 kg CO_2/t). The combined scenario demonstrates an intermediate value (148.5 kg CO_2/t), indicating the substantial influence of the road transport share on total emissions.

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INTRODUCTION

In the context of global climate change and the strengthening of international commitments to reduce greenhouse gas emissions, the decarbonization of industry has become a key issue for the sustainable development of national economies. Within the framework of the Paris Agreement, countries are developing long-term strategies to achieve carbon neutrality aimed at transforming energy, transport, and production systems.

The Republic of Kazakhstan, following the international climate agenda, has approved a strategy to achieve carbon neutrality by 2060, which provides a substantial reduction in emissions across all sectors of the economy, including industry and transport. This strategy sets the direction for the transition to low-carbon technologies and increases the need for quantitative assessment of emissions associated with industrial production and freight transportation.

In international practice, Life Cycle Assessment (LCA) provides a widely accepted framework for evaluating the environmental impacts of products and supply chains, including greenhouse gas emissions associated with transportation processes (ISO 14040 2006; ISO 14044 2006).

Within the European Union, the decarbonization policy of the construction sector implemented under the European Green Deal stimulates the use of wood-based materials as a low-carbon alternative to traditional materials.

China's construction sector has become an important focus of environmental assessment due to its substantial greenhouse gas emissions. Chen *et al.* (2022) used LCA to compare mass timber and concrete buildings and showed that long transport distances associated with timber supply chains significantly influence environmental impacts, highlighting logistics as an important contributor to transport-related environmental impacts.

Despite the prevalence of studies focused on the environmental assessment of wood-based materials and supply chains, the transportation phase is often addressed in general terms without a detailed analysis of alternative logistics scenarios. At the same time, the number of studies that take into account the regional characteristics of Central Asian countries and their dependence on imported sawn timber remains limited.

For the Republic of Kazakhstan, this issue is especially relevant, as the wood-processing industry largely depends on imported raw materials. The main supplies of sawn timber originate from Russia, primarily from Siberian regions. Transportation distances may reach 1,500 to 3,000 km, leading to significant transport-related emissions and transport-related CO_2 emissions throughout the timber supply chain .

Thus, in the context of implementing Kazakhstan's carbon neutrality strategy, there is a clear need for a quantitative assessment of transport-related CO_2 emissions associated with timber transportation and for the analysis of alternative logistics solutions. This necessity served as the starting point for the present study, which aimed to examine transport-related carbon emissions associated with imported timber supply and alternative logistics scenarios in Kazakhstan.

The objective of this study was to assess transport-related CO_2 emissions associated with sawn timber transportation to the city of Almaty and to conduct a comparative analysis of different transport scenarios, including rail, road, and combined transport. Particular attention is paid to the influence of logistics chain structure on CO_2 emission levels.

The scientific novelty of the study lies in the application of scenario-based comparative assessment of alternative timber transportation routes under the regional conditions of Kazakhstan and in quantifying the influence of transport mode and logistics chain configuration on transport-related CO_2 emissions.

The practical significance of the study lies in the possibility of using the obtained results to achieve reduction of transport-related greenhouse gas emissions, and to facilitate the selection of more sustainable timber transportation strategies, thereby contributing to Kazakhstan's national decarbonization objectives.

Literature Review

The industrial sector is one of the largest sources of global greenhouse gas emissions, accounting for a significant share of the overall carbon footprint associated with material production, construction, and building operation. In this context, the search for and implementation of low-carbon materials capable of ensuring sectoral decarbonization without compromising building performance has become particularly important.

Within this context, wood-based materials are considered one of the most promising options due to a combination of key environmental advantages: low production energy intensity, the ability to store carbon, and suitability for integration into circular production systems.

Chen *et al.* (2022) noted that wood products store biogenic carbon absorbed during tree growth, thereby delaying its release to the atmosphere over the product's lifetime. Petrović *et al.* (2024) showed that replacing virgin building materials with re-used wooden-based products substantially reduces greenhouse gas emissions and enhances the environmental performance of buildings.

Although wood is generally regarded as an environmentally favorable material, its overall environmental performance depends on multiple factors throughout the production chain. Costa *et al.* (2024) highlighted that methodological choices and manufacturing processes substantially influence the carbon footprint of wood-based panels. In addition, Arias *et al.* (2021) showed that synthetic formaldehyde-based adhesives contribute considerably to environmental impacts, which has stimulated the development of bio-based adhesive alternatives.

Atnoorkar *et al.* (2024) demonstrated that the environmental advantages of mass timber construction can be substantially reduced under long-distance supply chain scenarios. Their results show that transportation distances, sourcing locations, and processing facility locations strongly influence embodied carbon, emphasizing the need to evaluate wood products from a whole supply chain perspective.

Contemporary scientific literature demonstrates that wood-based materials have considerable potential to reduce the carbon footprint of the construction sector due to the combination of biogenic carbon storage, low production energy intensity, and the possibility of integration into circular systems. However, their actual environmental performance is determined by a complex set of factors, including material type, production technology, use of chemical components, and supply chain characteristics. In this regard, there is a clear need for a focused assessment of how logistics conditions influence the transport-related carbon emissions of wood raw material supply chains.

Carbon footprint assessment methods represent an important tool for the quantitative analysis of environmental impacts associated with production and transportation processes, including the supply of construction materials. In the transition toward a low-carbon economy, such approaches make it possible to evaluate transport-related emissions and identify the factors that most significantly influence the overall environmental performance of supply chains.

According to internationally accepted practice, LCA is based on the ISO 14040 (2006) and ISO 14044 (2006) standards, which define the analytical framework consisting of four main stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. This systemic approach ensures a comprehensive evaluation of environmental effects; however, its practical implementation is associated with a number of methodological and applied limitations.

At the same time, the reliability of LCA results depends heavily on the quality and consistency of Life Cycle Inventory (LCI) data. The LCI stage provides the material and energy flow information required for impact assessment. Hemmati *et al.* (2022) demonstrated that the use of different LCI databases, particularly Ecoinvent and GaBi, can produce substantial differences in estimated global warming potential due to variations in characterization factors and database structures.

The reasons for these discrepancies include differences in energy mixes (*e.g.*, the share of renewable energy sources), variations in technological processes, regional production characteristics, and differences in emission factors.

As a result, the same product may exhibit different carbon footprint values depending on the selected LCI database, limiting the comparability of LCA results across studies. Hemmati *et al.* (2022) therefore highlight the need for greater consistency, harmonization, and calibration of LCI databases and LCA software to improve the reliability and comparability of environmental assessments.

Another methodological challenge relates to the selection of system boundaries. Depending on the chosen approach (cradle-to-gate, cradle-to-grave, cradle-to-cradle), LCA results may differ significantly. This is particularly critical for wood-based materials, as excluding the use or end-of-life stages may lead to underestimation or overestimation of the carbon storage effect.

Gu *et al.* (2022) highlight the importance of explicitly including transportation processes within the system boundaries of cradle-to-gate LCA. Their case study showed that although transportation had a relatively small effect on global warming potential, it significantly influenced other environmental impact categories such as acidification, smog formation, and eutrophication. These findings demonstrate that transport-related processes should be considered when assessing the environmental performance of building materials.

In this context, it becomes evident that a proper assessment of wood-based materials requires consideration not only of production-related emissions, but also of transport emissions. This is particularly relevant for regions with extended logistical chains, where transportation can constitute a significant share of the total carbon footprint.

According to Atnoorkar *et al.* (2024), the production of mass timber involves multiple interconnected stages, including timber harvesting, lumber processing, transportation, CLT manufacturing, and delivery to the construction site. The authors demonstrate that greenhouse gas emissions are generated throughout these life-cycle stages and that transportation can substantially increase embodied energy and global warming potential, particularly when long transport distances are involved.

Bulková *et al.* (2025) compared the energy intensity and carbon emissions of road and rail freight transport and demonstrated that road freight generates substantially higher CO_2 emissions per tonne-kilometre than electrified rail transport. The study shows that the lower emissions of rail freight are associated with its substantially lower energy intensity and higher energy efficiency, whereas road transport relies on diesel fuel and exhibits considerably higher specific energy consumption.

Osorio-Tejada *et al.* (2024) further extended this perspective by developing an integrated LCA framework for transport systems, demonstrating that environmental impacts depend not only on the transport mode but also on vehicle load factors, road characteristics, traffic conditions, and infrastructure. Their findings emphasize the importance of service-specific transport modelling for improving the accuracy of environmental assessments.

Niu and Fink (2025) highlight that transport distance, vehicle type, and capacity utilization are commonly estimated during early-stage LCA because project-specific information is not yet available. Consequently, transport modelling becomes an important source of uncertainty in environmental assessment.

An analysis of contemporary literature indicates that transportation and logistics are among the key factors shaping the carbon footprint of wood-based materials. Despite the recognition of wood as a low-carbon resource, its environmental effectiveness can be substantially reduced under inefficient supply chain organization.

A critical review of existing studies allows for the formulation of several general conclusions:

- Transportation can account for a significant share of the total carbon footprint of wood-based materials, particularly over long distances;
- The choice of transport mode has a substantial impact on emission levels, with rail transport being more environmentally efficient than road transport;
- Supply chain optimization represents one of the most effective tools for carbon footprint reduction;
- Existing LCA approaches often insufficiently account for real logistics conditions, which reduces assessment accuracy.

Based on these findings, there is a clear need for detailed studies that consider specific transport routes, transport modes, and regional characteristics.

This is particularly relevant for long-distance logistics routes, such as the transportation of coniferous sawn timber from regions of Russia to the city of Almaty, where the choice of transport scheme can significantly affect the final carbon footprint of the products.

The conducted review of contemporary scientific literature on the environmental assessment of wood-based materials, LCA methodology, and transportation processes reveals several established research directions as well as important limitations of existing approaches. Despite the substantial volume of publications, a comprehensive understanding of the factors shaping the carbon footprint of wood-based materials remains fragmented.

Recent studies (Liu M. *et al.* 2025; Liu R. *et al*. 2025; Wedajo *et al*. 2025) indicate that wood has a relatively low carbon footprint and represents a viable alternative to conventional construction materials because of its capacity for biogenic carbon storage and its material substitution potential.

However, many existing studies primarily focus on material production and manufacturing processes, while transportation is treated as a secondary process or excluded from the system boundary altogether. Consequently, the influence of logistics on the overall carbon footprint of wood products remains insufficiently quantified, particularly for countries that rely on imported timber, such as Kazakhstan.

The lack of standardized LCI databases, region-specific emission factors, and harmonized methodological approaches leads to significant variability in results. This complicates cross-study comparisons and reduces their practical applicability.

Recent reviews highlight that transport logistics remains an underexplored component of environmental assessment in the construction sector. Russo *et al.* (2026) emphasize the need for more detailed analyses that explicitly consider transport modes, routing strategies, and logistics-related data in environmental assessment.

The reviewed literature demonstrates that considerable progress has been achieved in assessing the environmental performance of wood-based materials. Existing studies consistently show that wood generally exhibits a lower carbon footprint than conventional construction materials owing to its capacity for biogenic carbon storage, lower embodied emissions, and material substitution potential. At the same time, methodological advances in LCA have improved the quantification of environmental impacts across production systems and supply chains.

Despite these advances, several important limitations remain. Most existing studies primarily focus on material production and manufacturing processes, whereas transportation is frequently represented using generalized assumptions, averaged emission factors, or simplified logistics models. Consequently, the contribution of transport to the overall carbon footprint of wood products is often insufficiently characterized under real supply chain conditions.

These observations are consistent with the findings of a recent systematic review by Zhang *et al.* (2024), which concluded that transport-related life cycle assessment research still requires more region-specific analyses based on realistic transport routes and logistics conditions, particularly for improving the representation of transport systems in environmental assessment.

In addition to these methodological limitations, the spatial scope of existing assessments also remains limited. Most published studies examine transport emissions under generalized or national-scale supply chain conditions, whereas region-specific analyses based on actual transport routes remain limited.

Existing studies recognize the importance of transport-related emissions but rarely compare alternative logistics configurations for imported timber supply using consistent functional units and route-specific transport data. Consequently, the environmental implications of selecting alternative transport modes remain insufficiently quantified under actual supply conditions.

These limitations are especially relevant for Kazakhstan, where the wood-processing industry relies predominantly on imported sawn timber transported over long distances from neighboring countries. Under such conditions, generalized transport assumptions may not adequately represent actual logistics systems or support evidence-based decisions aimed at reducing transport-related carbon emissions.

To address this research gap, the present study performs a route-specific assessment of transport-related CO_2 emissions associated with imported sawn timber supplied to Almaty. Three representative logistics scenarios-rail, road, and combined transport-are evaluated using identical functional units and representative transport distances for imported timber supply from Russia to Almaty.

Unlike generalized assessments, this study provides a quantitative comparison of alternative logistics configurations for the same transport route, allowing the influence of transport distance, transport mode, and logistics chain structure on transport-related carbon emissions to be evaluated consistently. The findings provide a quantitative basis for evaluating alternative timber transport configurations and support evidence-based logistics planning for reducing transport-related CO_2 emissions in Kazakhstan.

EXPERIMENTAL

An analysis of transport infrastructure and trade flows indicates that rail transport is the dominant mode for sawn timber shipments from Russia to Kazakhstan, accounting for up to 68% of the country's freight turnover. Transport operations are conducted *via* a network of cross-border railway checkpoints connecting the transport systems of Russia and Kazakhstan. Road transport is also carried out through officially designated international border crossings, including Kairak, Zhana Zhol, and Sharbakty, depending on the origin of the shipment and the selected logistics route.

Based on the existing transport infrastructure and prevailing freight transport practices, three representative logistics scenarios were developed to represent the principal options for imported timber deliveries from Russia to Almaty. These scenarios constitute the analytical framework for comparing transport-related CO_2 emissions under alternative logistics configurations.

This study quantitatively assessed transport-related CO_2 emissions associated with imported timber supply using a carbon emission assessment approach combined with a comparative analysis of representative logistics scenarios.

A scenario-based methodology was employed to compare the transport-related carbon emissions of the representative logistics configurations under equivalent transport conditions. This approach enables evaluation of the influence of transport mode and logistics chain structure on the overall transport-related carbon footprint. This study focused exclusively on the transportation stage of the timber supply chain. The quantitative assessment covers CO_2 emissions associated with the transportation of sawn timber from the sawmill to a warehouse in Almaty under alternative logistics scenarios. Emissions from timber harvesting, primary processing, product manufacturing, intra-urban logistics, use, and end-of-life stages were outside the scope of this study and were therefore not included in the quantitative assessment.

Such a transport-specific system boundary is consistent with recent methodological recommendations emphasizing that environmental assessments should define system boundaries according to the specific objective of the study to ensure transparency and comparability of the results (Ling *et al*. 2024)

Accordingly, the analysis focuses on the influence of alternative logistics scenarios on transport-related CO_2 emissions associated with timber supply to Almaty. The functional unit is defined as 1 tonne of sawn timber delivered to the city of Almaty. This functional unit was selected because transport emission factors are commonly expressed in kilograms of CO_2 per tonne-kilometre (kg CO_2/t·km), ensuring direct compatibility with internationally recognized emission factors. Although cubic metres (m^3) are frequently used in studies of wood products, a mass-based functional unit is more appropriate for transport emission assessment because freight transport emission factors are defined on a mass-distance basis, and vehicle fuel consumption is primarily determined by cargo weight rather than its volume. This choice also enables consistent comparison of alternative transport scenarios.

For the analysis, three representative transport scenarios were developed to reflect the principal logistics configurations for imported timber deliveries from the Russia to Almaty (Table 1).

Table 1. Transportation Scenarios and Parameters

No.	Scenario	Route	Transport Mode	Distance (km)	Emission Factor (kg CO_2/t·km)
1	Scenario 1	Irkutsk → Almaty	Rail	3100	0.02
2	Scenario 2	Tyumen → Almaty	Road	1700	0.09
3	Scenario 3	Irkutsk → Pavlodar (Rail) → Almaty (Road)	Combined	2700 (rail) + 1050 (road)	0.02 / 0.09

The scenarios were designed to represent rail, road, and multimodal transport alternatives commonly used in cross-border timber transportation. They do not represent all possible delivery routes but provide a consistent basis for comparing transport-related CO_2 emissions under different logistics configurations.

The carbon footprint of transportation was calculated using a distance-based model:

$$E = m \cdot d \cdot EF \tag{1}$$

where E is transport-related CO_2 emissions (kg), m is cargo mass (t), d transport distance (km), and EF is emission factor (kg CO_2/t·km).

For the combined scenario, emissions were calculated as the sum of emissions for each transport mode, as shown in Eq. 2.

$$E = m \cdot (d_{rail} \cdot EF_{rail} + d_{road} \cdot EF_{road}) \tag{2}$$

The calculations use average emission factors consistent with international practices for carbon footprint assessment and transportation emissions analysis (Table 2).

Table 2. Emission Factor Values, kg CO_2/t·km

No.	Transport Mode	IPCC (kg CO_2/t·km)	Ecoinvent (kg CO_2/t·km)	Average Value (kg CO_2/t·km)
1	Rail transport	0.015 to 0.03	0.015 to 0.025	0.02
2	Road transport	0.06 to 0.12	0.07 to 0.11	0.09

Table 2 presents emission factor ranges for different transport modes based on the Intergovernmental Panel on Climate Change (IPCC) and Ecoinvent databases. The values reported by different sources fall within comparable ranges. In the present study, averaged values were applied (0.02 kg CO_2/t·km for rail transport and 0.09 kg CO_2/t·km for road transport), ensuring representativeness and cross-scenario comparability.

The following assumptions were adopted in the modeling process: (1) transport vehicles operate under standard load conditions; (2) routes are linear and deviations are not considered; and (3) emissions are calculated without accounting for empty return trips.

The limitations of the study include the use of averaged emission factors, lack of detailed data on specific suppliers, and simplified representation of logistics chains.

Scenario comparison was conducted based on absolute CO_2 emission values (kg/t) and relative differences between scenarios.

These parameters allow identification of the most environmentally efficient transportation option.

RESULTS AND DISCUSSION

Transport Scenario Comparison

The case-based modelling approach enabled comparison of representative logistics configurations under equivalent transport conditions. The analyzed scenarios reflect typical transport alternatives available for imported timber deliveries to Almaty and demonstrate the influence of transport mode and logistics chain structure on transport-related CO_2 emissions.

Scenario 1 - Rail transport (Irkutsk → Almaty)

Timber is produced at a forest-industry enterprise in Eastern Siberia (Irkutsk region) and shipped to Kazakhstan by rail. The route passes through Irkutsk, Krasnoyarsk, Omsk, Pavlodar, and Almaty. Transportation is carried out within freight railway trains.

Scenario 2 - Road transport (Tyumen → Almaty)

Timber is supplied from Western Siberia (Tyumen region) by road transport. Delivery is performed via cross-border checkpoints. The route includes Tyumen, Kurgan, Kostanay, Karaganda, and Almaty.

Scenario 3 - Combined transport

In this scenario, rail delivery is used from Irkutsk to Pavlodar, followed by road delivery from Pavlodar to Almaty.

Table 3. Case Study Results for 1 t of Sawn Timber (kg/t)

No.	Scenario	Calculation	CO_2 Emissions (kg/t)	Relative Level
1	Rail	3100 × 0.02	62	100%
2	Road	1700 × 0.09	153	247%
3	Combined	(2700×0.02)+(1050×0.09)	148.5	240%

Rail transport demonstrates the lowest CO_2 emission level (62 kg/t), which is explained by its high energy efficiency and low emission factor (Table 3).

Road transport exhibits the highest emission level (153 kg/t), exceeding the rail option by 91 kg CO_2/t or 147%. Despite the shorter transport distance, this scenario remains the most carbon-intensive.

The combined scenario results in emissions of 148.5 kg CO_2/t, slightly lower than road transport but significantly higher than rail transport. The difference relative to rail transport amounts to 86.5 kg CO_2/t (140%) (Table 4).

Table 4. Comparative Analysis of Transport Scenarios (1 tonne), %

No.	Scenario	Transport Mode	CO_2 Emissions (kg/t)	Deviation from Rail (kg)	Relative Increase (%)
1	Scenario 1	Rail	62	0	0%
2	Scenario 2	Road	153	+91	+147%
3	Scenario 3	Combined	148.5	+87	+140%

The comparative analysis reveals the following patterns:

- An increased share of road transport leads to higher CO_2 emissions;
- Shorter distances do not compensate for the high carbon intensity of road transport;
- Combined schemes may reduce emissions relative to road transport but remain less efficient than rail transport due to the presence of a high-carbon road segment and additional logistics operations (Fig. 1).

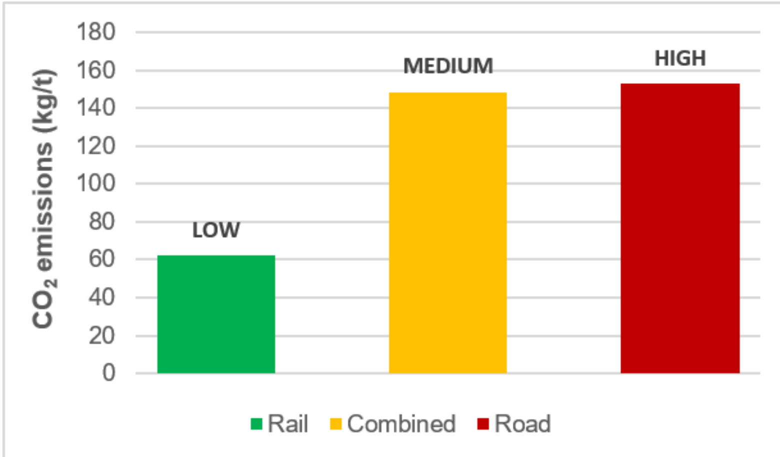

Fig. 1. Comparison of CO_2 emissions under different transport scenarios

Under the modeled conditions, transport mode selection appeared to have a stronger influence on transport-related CO_2 emissions than transport distance alone. Although the road scenario involves a substantially shorter route than the rail scenario, its higher emission factor results in more than twice the transport-related CO_2 emissions. This highlights the importance of considering transport mode alongside transport distance when designing low-carbon timber supply chains.

This interpretation is consistent with recent transport emission studies indicating that transport mode selection and transport distance are the primary determinants of freight transport emissions, with optimization of transport configuration representing an effective strategy for reducing environmental impacts (Yang *et al.* 2025).

The analysis confirms that rail transport is the most environmentally efficient method for delivering timber to Almaty. The combined scenario can be considered an intermediate solution; however, its environmental performance is largely determined by the length of the road segment. Road transport remains the least preferable option in terms of transport-related CO_2 emissions. Increasing the share of rail freight transport could substantially reduce transportation-related carbon emissions associated with timber imports to Kazakhstan without changing raw material sources.

Sensitivity Analysis

Sensitivity analysis supports the results of the comparative assessment, showing that absolute emission values vary depending on emission factors, with changes of up to ±30%. However, under all parameter values, the relative ranking of scenarios remains unchanged. This confirms the robustness of the findings and the validity of the conclusions (Table 5).

Table 5. Sensitivity Analysis Results for CO_2 Emissions under Alternative Transport Scenarios

No.	Scenario	Minimum (kg/t)	Base Case (kg/t)	Maximum (kg/t)
1	Rail	46	62	93
2	Road	102	153	204
3	Combined	~110	148.5	~190

Note: All values represent transport-related CO_2 emissions only and do not include other greenhouse gases expressed as CO_2-equivalent.

The reported results apply only to the transport routes and assumptions considered in this study.

Comparison with Previous Studies

The results obtained are consistent with recent studies on the carbon footprint of wood-based building materials. Numerous studies have shown that, although wood generally exhibits a lower carbon footprint than conventional construction materials, its environmental performance is strongly influenced by transportation and supply chain characteristics. In particular, Hemmati *et al.* (2022) demonstrated that transport-related processes constitute an important component of the carbon footprint of timber products, whereas Kaulen *et al.* (2024) showed that transport-related emissions increase substantially with transport distance and are influenced by the selected transport configuration.

The present findings further support the findings of recent studies that the transportation stage is one of the key factors in carbon emissions within the wood product supply chain.

The scenario analysis agrees with previous studies demonstrating the environmental advantages of rail freight transport. Scenario-based modelling by Wen and Song (2022) showed substantially lower carbon emissions for rail freight than for road transport, while recent review studies (Giunta 2023; Wang *et al*. 2024) reached the same conclusion through the synthesis of published evidence.

A distinctive feature of this study is its focus on Kazakhstan, where the wood-processing industry relies predominantly on imported timber from Russia. Under these conditions, transportation logistics becomes a critical factor influencing transport-related CO_2 emissions. Therefore, this study provides region-specific evidence on how transport distance, transport mode, and logistics chain configuration affect transport-related emissions associated with imported timber supply, thereby supporting more informed logistics planning for import-dependent regions.

Implications for Sustainable Material Production

The study has important implications for improving the environmental performance of imported timber supply and supporting low-carbon wood processing in Kazakhstan.

The study shows that the environmental performance of wood-based materials is not absolute and is also strongly influenced by transport distance, transport mode, and logistics chain configuration. Even materials with low energy-intensive production can have a significant carbon footprint when transported over long distances.

The analysis also highlights Beyond the direct comp the importance of incorporating transport-related CO_2 emissions into timber supply planning and logistics decision-making.

Within the scenarios examined, rail transport demonstrated the greatest potential for reducing transport-related CO_2 emissions associated with imported timber supply.

These findings are consistent with Kazakhstan's broader strategy for achieving carbon neutrality by 2060 and promoting sustainable industrial development.

In addition, the study’s findings can be used:

- Transport mode selection;
- Evaluation of alternative logistics configurations;
- Route planning for imported timber;
- Evidence-based logistics decision-making for timber supply.

Overall, incorporating route-specific transport emission assessment into timber supply planning provides a quantitative basis for comparing alternative logistics configurations and reducing transport-related CO_2 emissions associated with imported timber supply.

Environmental Implications of Long-distance Timber Transportation

Beyond comparing the transport scenarios, this study also has broader implications for sustainable material production in import-dependent and landlocked regions.

Previous life cycle assessment studies have shown that transportation emissions can account for a substantial share of a product's life-cycle carbon footprint, particularly in long and import-dependent supply chains.

Atnoorkar *et al.* (2024) demonstrate that the carbon intensity of mass timber materials is strongly influenced by raw material sourcing and transport distances, with transportation representing an important determinant of life-cycle environmental performance. Kühmaier et al. (2022) demonstrated that timber transport represents the largest source of greenhouse gas emissions within the forest supply chain. Their results further showed that longer transport distances increase emissions, while rail transport exhibits substantially lower carbon intensity than roundwood truck transport. Together, these studies indicate that transport distance and logistics configuration are major determinants of transport-related environmental performance, reinforcing the importance of route-specific assessments under regional supply conditions

Unlike locally produced concrete, the supply chain for imported sawn timber used in Kazakhstan is characterized by a high dependence on imports from the Siberian regions of Russia. As a result, the transportation of sawn timber often involves long-distance rail routes followed by road delivery stages, leading to increased transportation emissions. In some cases, the transportation distance typically ranges from approximately 1,500 to 3,000 km before the raw materials arrive at processing plants in Almaty.

The results show that when choosing between eco-friendly wood-based building structures and concrete structures, the environmental advantages of wood-based materials should be evaluated within their specific regional and logistical context. For import-dependent landlocked countries in Central Asia, the transportation system and the configuration of the logistics chain can significantly alter transport-related CO_2 emissions associated with wood products and their environmental competitiveness compared to locally produced concrete materials.

The practical significance of the study lies in the applicability of the results for optimizing timber supply chains in Kazakhstan. Expanding the use of rail transport and reducing reliance on road transport can significantly reduce transport-related CO_2 emissions associated with timber supply and support national decarbonization objectives.

The limitations of the study are related to the use of averaged emission factors and simplified representations of logistics scenarios. Future research should incorporate more detailed transport flow data, route-specific operational information, and extend the system boundaries to include warehousing, urban distribution, and subsequent life cycle stages.

CONCLUSIONS

1. This study analyzed transportation-related CO_2 emissions associated with the delivery of imported sawn timber to Almaty, within the context of Kazakhstan's strategy to achieve carbon neutrality by 2060. Particular attention was paid to assessing the influence of logistics scenarios and transport modes on CO_2 emissions.
2. The results demonstrate that the transportation represents a major source of transport-related CO_2 emissions within timber supply chains under conditions of extended transport distances. Comparison of three transport scenarios revealed that rail transport provides the lowest emission level - 62 kg CO_2/t - whereas road transport is characterized by significantly higher carbon intensity - 153 kg CO_2/t. The combined scenario, incorporating both rail and road segments, exhibits an intermediate value of 148.5 kg CO_2/t, confirming the substantial influence of the road transport share on transport-related CO_2 emissions.
3. Sensitivity analysis showed that varying emission factors within international ranges alters absolute emission values but does not affect the relative ranking of scenarios. In all cases, rail transport remains the most environmentally efficient option, demonstrating the robustness of the obtained results.
4. For the examined Kazakhstan timber logistics case, the results demonstrate that logistics chain configuration and the share of different transport modes exerted a greater influence on transport-related CO_2 emissions than route distance alone. This underscores the need for a more detailed analysis of logistics scenarios and supply chains when assessing transport-related CO_2 emissions associated with timber supply.
5. The environmental benefits of wood-based materials are not universal and must be considered in light of regional supply conditions and the characteristics of the transportation infrastructure. In Kazakhstan, where the woodworking industry relies heavily on imported raw materials, transport-related CO_2 emissions become a critical factor in the environmental assessment of timber supply systems. The results confirm the need to account for logistics when conducting transport-related environmental assessments and selecting more sustainable supply options.

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Conflict of Interest

The authors declare no conflict of interest.

Use of Generative AI

The authors used ChatGPT (OpenAI) as a supplementary tool during the preparation of the manuscript. The tool was used to assist with language editing, improvement of English writing, grammar checking, refinement of wording and sentence structure, organization of the literature review, and preparation of selected text fragments.

All references were independently selected, verified, and reviewed by the authors using the original publications. The authors critically evaluated and revised all text generated with the assistance of artificial intelligence tools.

Artificial intelligence tools were not used for data collection, data generation, data

analysis, preparation of figures, calculation of results, or interpretation of research findings. All scientific conclusions, methodological decisions, and manuscript content were developed, verified, and approved by the authors.

The authors take full responsibility for the accuracy, integrity, and originality of the manuscript.

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