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Shaping a Sustainable Future: How Energy Consumption and Carbon Emissions Drive Low-Carbon Development

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ABSTRACT

Research Originality: The study examines the impact of deforestation, energy use, transportation, and industrialization in North Sumatra from 1991 to 2021 on low-carbon development. It aims to understand environmental change drivers and propose strategies to mitigate their negative effects on development.

Research Objectives: This research aims to explore the relationship between deforestation, energy consumption, land transportation, and industrialization as factors influencing low-carbon development.

Research Methods: The study examines factors influencing low-carbon development in North Sumatra from 1991 to 2021, including energy consumption, land transportation, industrialization, and deforestation, influenced by population density and property rights.

Empirical Results: The study reveals that deforestation, energy consumption, land transportation, and industrialization significantly impact low-carbon development in North Sumatra, with population density positively influencing deforestation.

Implications: The research suggests that the government should implement policies to reduce deforestation, increase public transportation usage, and promote electric vehicles to achieve low-carbon development, promote efficient energy consumption, and encourage environmentally friendly technological innovation.

Keywords:

carbon emissions; deforestation; energy consumption; low-carbon development

How to Cite:

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INTRODUCTION

The pursuit of welfare is a fundamental goal for individuals, encompassing income and satisfaction derived from the benefits of economic activities. To achieve this, governments promote economic development to enhance social wealth and community welfare. However, it is essential that this economic growth is pursued sustainably, considering environmental impacts. Sustainable economic development requires balancing capital, human, and natural resources while integrating social, institutional, and political aspects (Jie & Lan, 2024). Low-carbon development is one such approach that seeks to reduce emissions, promote economic growth, and mitigate poverty. Cutting emissions can increase economic growth while improving air quality and living standards and reducing mortality rates (Mahalik et al., 2022).

Natural resources, which should be an asset for governments, can sometimes hinder low-carbon development if their utilization leads to environmental degradation. Deforestation, for instance, is a significant issue that can arise from excessive resource exploitation and land conversion (Qamruzzaman, 2024). Clearing forests produces carbon emissions, primarily through burning, contributing to climate change. North Sumatra, with a population of over 15 million, faces challenges in achieving low-carbon development due to its dense population and the environmental impacts of economic activities.

Under regional autonomy, local governments in North Sumatra work to improve community welfare and alleviate poverty through economic development that supports sustainable goals. However, such development, mainly through natural resource use, can negatively impact the environment and hinder low-carbon objectives (Hariram et al., 2023). Deforestation is one such environmental issue, as shown by the trends in carbon emissions and deforestation between 2016 and 2021. Key factors contributing to carbon emissions include energy consumption, transportation, industrialization, and deforestation (Hoa et al., 2024).

The relationship between carbon emissions and deforestation in North Sumatra is complex. Energy consumption, mainly from fossil fuels, contributes significantly to carbon emissions. Similarly, land transportation and industrialization also play a role, with the transportation sector crucial for economic activities and contributing to emissions. Deforestation, however, is the most direct environmental issue, with its impacts including climate change, biodiversity loss, and the risk of natural disasters such as floods and landslides. Studies from various regions, such as China, Brazil, and Russia, highlight the interplay between economic growth, deforestation, and environmental sustainability, emphasizing policies that promote balanced growth while protecting forest resources (Li et al., 2022). Several key factors drive deforestation in North Sumatra. Agricultural expansion for commodities like palm oil, rubber, and food crops leads to forest clearance. Illegal logging and unsustainable timber extraction also contribute significantly. The growing population demands more land for housing and agriculture, further encroaching on forests. Infrastructure development, like roads, increases forest access, promoting exploitation. Weak government policies and inconsistent enforcement allow for continued deforestation. Climate change stresses ecosystems, making forests more vulnerable, while land tenure

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conflicts between local communities, the government, and businesses further exacerbate the problem. These factors combine to create a complex issue that requires comprehensive solutions. Table 1 shows the variable influence of deforestation in North Sumatra.

Table 1. Variables Suspected to Influence Deforestation in North Sumatra

Year	Population density (%)	Property rights (%)	Industrialization (%)
2016	1,05	2,68	5,05
2017	1,55	4,94	2,31
2018	1,02	10,68	3,66
2019	1,01	7,35	1,23
2020	1,50	6,38	-0,84
2021	0,49	6,32	1,43

Sources: Badan Pusat Statistik (BPS)

The increasing population from year to year can also cause deforestation, especially in rural areas where people without fixed livelihoods tend to utilize forests to earn a living. Property rights also play a crucial role, as land ownership rights must be established to prevent loopholes for deforestation actors. This condition is also related to the formation of capital and the extent of forests, and these are large-scale economic factors that can impact the extent of deforestation.

Najicha et al. (2023) explain the transition to sustainable energy management and its importance in mitigating the impact of fossil fuel consumption, which currently accounts for 73% of greenhouse gas (GHG) emissions in the energy sector. The focus is on policy changes and implementing renewable energy solutions supported by legal and regulatory frameworks. It emphasizes the global significance of green investments in renewable energy and the need for harmonizing legislation and technical standards to achieve sustainable development effectively. The study points out that while the energy management model has become more dynamic and adaptable through intelligent monitoring and control, there is still a gap in its optimal implementation (Najicha et al., 2023).

According to Androniceanu et al. (2024) technological advancements and the evolution of public policies supporting energy transitions drive the growing importance of sustainable energy. It uses bibliometric analysis to track trends in research from 1991 to 2024, focusing on the intersections of sustainable energy, renewable energy, and sustainable development. The study underscores the increasing collaboration in research, the significance of high-impact journals in shaping sustainability policies, and the growing emphasis on renewable energy and CO2 emissions. By analyzing these themes, the paper highlights emerging trends in environmental policy and calls for formulating coherent sustainability strategies.

Both studies emphasize the importance of sustainable energy transitions but with a focus on policy, research, and technological advancements. This study comprehensively analyzes the relationship between deforestation, energy consumption, transportation, and industrialization in North Sumatra from 1991 to 2021. It stands out from previous

research by examining how these factors interact over time in a specific regional context rather than in isolation. Previous studies have focused on global or national levels, whereas this research provides a localized understanding of North Sumatra's unique challenges (Stacey et al., 2021). The study fills a gap in the literature by exploring the combined impacts of these factors on low-carbon development, with particular attention to local governance and policy initiatives aimed at mitigating deforestation.

The study's contribution lies in its integrated model for low-carbon development in North Sumatra, which incorporates factors such as energy use, land transportation, industrialization, and deforestation. It emphasizes the need for policies addressing the complex interactions between these variables to achieve environmental and economic sustainability. The research provides valuable insights for local governments and policymakers, offering actionable recommendations for promoting sustainable growth while minimizing environmental degradation. Ultimately, the study aims to help achieve low-carbon development goals in North Sumatra and offers potential applications for other regions facing similar challenges. Unlike previous studies focusing on global or national scales and isolated factors, this study offers a localized analysis, highlighting the interactions between these factors in a specific region. Its novelty lies in developing an integrated model for low-carbon development, which provides actionable insights for local governments and policymakers to achieve sustainable growth while minimizing environmental degradation.

METHODS

The data used in this research is secondary data collected from the Central Statistics Agency of North Sumatra, covering a period of 31 years. This extensive time frame allows for a thorough analysis of the long-term trends and relationships between various factors that influence low-carbon development in the region. Figure 1 shows the conceptual framework from this research. The key variables studied in this research include:

1. Low-carbon development (Y1): Represented by the low-carbon development index, which tracks the region's progress in reducing carbon emissions while promoting sustainable economic growth.
2. Deforestation (Y2): Measured by the deforestation area in hectares, reflecting the extent of land-use changes and the impact of deforestation activities.
3. Energy consumption (X1): Represented by the fuel consumption volume in kiloliters, which indicates the demand for fossil fuels, a major contributor to carbon emissions.
4. Land transportation (X2): Measured by the number of registered land vehicles, indicating the transportation sector's role in carbon emissions.
5. Industrialization (X3): Represented by the GDP value of the industrial sector in Rupiah, reflecting the level of industrial activity and its contribution to carbon emissions.
6. Population density (X4): Represented by the population density figure, which is a demographic factor influencing land use and resource consumption.
7. Property rights (X5): Measured by the number of land ownership certificates, which can affect land management and contribute to deforestation.

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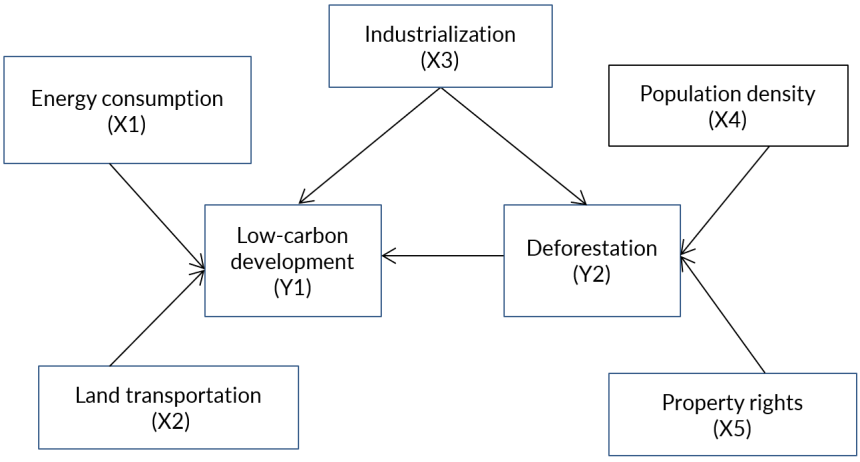
The secondary data from these indicators provide a comprehensive set of variables to examine how various socio-economic and environmental factors interact to influence low-carbon development in North Sumatra.

Figure 1. Conceptual framework



The analysis in this research employs quantitative methods, using both descriptive and associative techniques to understand the relationships between the variables (Kotronoulas et al., 2023).

1. Descriptive Analysis: This approach helps in summarizing the data and providing an overview of the trends in each of the variables over the 31-year period. It will present the general patterns and provide context for understanding how each factor has evolved.
2. Associative Analysis: This method is used to analyze the relationships between the variables and understand how they affect each other. The key to this analysis lies in the regression models that are mathematically represented by the equations:
   - Equation 1:

     $$Y_{1t} = \alpha_0 + \alpha_1 \hat{Y}_{2t} + \alpha_2 X_{1t} + \alpha_3 X_{2t} + \alpha_4 X_{3t} + \varepsilon_{1t}$$

     This equation examines the relationship between low-carbon development (Y1) and the independent variables: deforestation area (Y2), energy consumption (X1), land transportation (X2), and industrialization (X3), with ε_{1t} representing the error term.
   - Equation 2:

     $$Y_{2t} = \alpha_5 + \alpha_6 X_{3t} + \alpha_7 X_{4t} + \alpha_8 X_{5t} + \varepsilon_{2t}$$

     This equation investigates the influence of industrialization (X3), population density (X4), and property rights (X5) on deforestation area (Y2), with ε_{2t} as the error term.
3. The regression models aim to quantify how the various factors influence the dependent variables (low-carbon development and deforestation), allowing for a deeper understanding of their causal relationships.

Table 2. Research variable indicators

No	Variables	Indicators	Unit
1	Low-carbon development (Y1)	Low-carbon development index	Index
2	Deforestation (Y_2)	Deforestation area	Hectares
3	Energy consumption (X1)	Fuel consumption volume	Kiloliter
4	Land transportation(X2)	The number of registered land vehicles	Unit
5	Industrialization (X3)	GDRP value of the industrial sector	Rupiah
6	Population density (X4)	Population density figure	People
7	Property rights (X5)	The number of land ownership certificates	Unit

Statistical analysis tools such as multiple regression analysis will likely be used to test the significance of these relationships and evaluate the strength of the influence each factor has on the outcome variables. These tools provide a way to measure and validate the hypotheses that different factors, such as energy consumption or deforestation, are related to developing a low-carbon economy in North Sumatra (Gunawan et al., 2024). The research combines descriptive methods to summarize data trends and associative methods, specifically regression analysis, to explore the relationships between energy consumption, industrialization, land transportation, deforestation, and low-carbon development. These analytical tools will help provide insights into the complex dynamics in North Sumatra's pursuit of sustainable, low-carbon growth.

RESULTS AND DISCUSSION

It is important to understand that this equation models the relationship between energy consumption, carbon emissions, and economic growth. It aims to assess how different strategies, such as energy efficiency improvements and the adoption of renewable energy, contribute to reducing carbon emissions while supporting economic development. The results, obtained using Eviews software, help analyze these relationships and guide policies for achieving sustainable, low-carbon growth. Now, let us look at the estimated results. The estimated results of the low-carbon development equation process are displayed in Table 3.

Table 3. Estimated Results of the Low-Carbon Development

Variabel	Coefficient	Std. Error
C	2,378527	2,018432
$\hat{Y}_2$	-0,217227	0,051796
$Log(X_1)$	-0,023216	0,030400
$Log(X_2)$	-0,363617	0,107216
$Log(X_3)$	-0,352933	0,213409

Note: Significant at 5%
Sources: Data processing results with Eviews

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From the estimation conducted, the model of the low-carbon development equation in this study is as follows:

$$Y = 2{,}378 - 0{,}217\ \hat{Y}_2 - 0{,}023\log(X1) - 0{,}363\log(X2) - 0{,}352\log(X3)$$

The results of the processed data indicate that deforestation, energy consumption, land transportation, and industrialization significantly impact low-carbon development in North Sumatra. Partially, deforestation has a significant influence on low-carbon development in North Sumatra. Deforestation is an activity that results in the reduction of forest or tree cover, which is expected to produce oxygen needed by humans and absorb carbon dioxide. With the expansion of deforestation, the number of plants acting as carbon emission absorbers will decrease, thus increasing the amount of carbon emissions released.

The low-carbon development equation estimated reveals that all these factors collectively explain about 51% of the variation in low-carbon development, as indicated by the R-squared value of 0.5107. The F-statistic of 6.7853, shows that the model is statistically significant, confirming the relevance of the independent variables in shaping the trajectory of low-carbon development in the region. Among the factors examined, deforestation emerged as a particularly influential variable. The negative coefficient of deforestation demonstrates that deforestation has a substantial adverse effect on low-carbon development. This finding aligns with the work of Raihan and Tuspekova, who argued that deforestation leads to a decrease in the number of carbon-absorbing plants, thereby exacerbating carbon emissions (Raihan & Tuspekova, 2022). The results are also consistent with those of Duchelle et al. (2018), who identified reducing deforestation as one of the key strategies for achieving low-carbon development by mitigating carbon emissions from forest degradation. In the case of North Sumatra, deforestation continues to contribute significantly to carbon emission levels, and this study underscores the need for stricter enforcement of forest protection policies and the promotion of reforestation initiatives to reduce environmental degradation and enhance carbon sequestration.

Energy consumption also plays a crucial role in low-carbon development. The negative coefficient suggests that higher energy consumption is linked to more significant carbon emissions by hindering low-carbon development. This result is consistent with the findings of Yang et al. (2024), who highlighted the environmental consequences of increased energy consumption, mainly from fossil fuels like coal. Raihan et al. also emphasized that the growing demand for energy-intensive products and services contributes to increased carbon emissions (Raihan et al., 2023). In North Sumatra, where energy consumption is closely tied to fossil fuel use, this presents a significant challenge to achieving a low-carbon economy. The study suggests a transition toward cleaner energy sources, such as solar, wind, and hydroelectric power, as well as improvements in energy efficiency through the adoption of energy-saving technologies.

Land transportation is another significant factor influencing low-carbon development. The estimated coefficient indicates that land transportation contributes substantially to carbon emissions, thus obstructing low-carbon development efforts. This result is in line with the study by Wang et al. (2024), which suggested that reducing transportation

frequency and improving transportation efficiency could help reduce carbon emissions. The increasing number of vehicles and reliance on gasoline-powered transportation in North Sumatra contribute to higher carbon emissions, which hinder the region's transition to a low-carbon economy. This study proposes enhancing public transportation infrastructure, promoting the use of electric vehicles, and adopting fuel-efficient technologies. Encouraging shared mobility and transitioning from conventional gasoline-powered vehicles to electric vehicles could significantly reduce emissions from the transportation sector, aligning with global efforts to promote low-carbon development (Choudhari et al., 2024).

Finally, industrialization has a negative effect on low-carbon development in North Sumatra. Industrialization, which often relies on fossil fuels for energy, results in increased greenhouse gas emissions, primarily carbon dioxide. This issue is particularly pressing in North Sumatra, where industrialization is accelerating. The study emphasizes the need for policies that encourage cleaner industrial technologies, greater energy efficiency, and adoption of green technologies. Additionally, carbon pricing mechanisms, such as carbon taxes or emission trading schemes, could provide the necessary economic incentives for industries to reduce emissions and transition toward sustainable practices (Mehmood et al., 2024).

The results of hypothesis testing for the deforestation equation typically assess whether the independent variables (e.g., economic factors, government policies, or land use) significantly impact deforestation rates. A p-value lower than the chosen significance level indicates that the independent variables statistically affect deforestation. If the null hypothesis (suggesting no effect) is rejected, it suggests that the factors studied are indeed influencing deforestation. Conversely, if the p-value is higher than 0.05, the evidence is insufficient to conclude a significant impact, implying that the variables may not be driving deforestation in the analyzed context. The estimated results of the deforestation in the equation analyzed are displayed in Table. 4.

Table 4. Estimation results of the deforestation equation

Variabel	Coefficient	Std. Error	R-squared	F-Statistic
C	57.95469	31.25364	0.6574	17.2712
$Log(X_3)$	3.376397	3.986480		
X_4	0.977409	0.421839		
$Log(X_5)$	-0.016146	0.085224		

Note: Significant at 5%
Sources: Data processing results with Eviews

The estimation results from the deforestation equation analyzed offer valuable insights into the factors influencing deforestation in North Sumatra. The estimated equation from the study is as follows:

$$Y = 57{,}954 + 3{,}376\log(X3) + 0{,}977X4 - 0{,}016\log(X5)$$

Where Y represents the rate of deforestation, X3 stands for industrialization, X4 indicates population density, and X5 represents land ownership rights. The model reveals that industrialization, population density, and land ownership collectively influence deforestation

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in North Sumatra. The F-statistic yielded a probability value of 0.000, indicating that the overall model is statistically significant. However, when examining the individual variables, industrialization was found to have no significant impact on deforestation, with a p-value of 0.4045. The test result on the R-squared value shows the value of 0.6574, which means the estimation results of the deforestation equation are considered good. This result suggests that industrialization is not currently a primary driver of deforestation in the region, possibly due to the growing adoption of efficient technologies and sustainable practices within industries. As industries begin implementing more eco-friendly methods, such as prioritizing recycling and improving waste management, the demand for natural resources, including wood, is reduced, thereby mitigating the pressure on forests (Mehmood et al., 2024). This finding aligns with Sunny et al. (2025), who pointed out that while industrial economic rent might increase deforestation in the short term, sustainable industrial practices can counterbalance this effect. Furthermore, Ehigiamusoe et al. (2023) support the view that industrialization can reduce deforestation with proper industrial location selection, adherence to environmental regulations, and effective waste management strategies.

On the other hand, population density was found to significantly influence deforestation. The value suggests that the pressure on forest resources increases as population density increases. This result is primarily due to the increased demand for wood for construction and fuel, as well as the need for agricultural land and settlement expansion. Population growth leads to higher demand for forest products, increasing deforestation rates. The increased demand for forest products and land use often results in more trees being cut down to meet the expanding needs of the population. While population pressure initially leads to higher deforestation rates, long-term efforts to improve agricultural practices, increase land-use efficiency, and enhance productivity could slow down these rates and allow for the sustainable management of forest resources.

In contrast, land ownership rights were found to have no significant effect on deforestation. Despite expectations that straightforward and secure property rights would encourage better land management and forest conservation, the findings suggest that landowners in North Sumatra are often motivated by economic pressures to exploit forest resources. In many cases, landowners do not comply with regulations prohibiting deforestation, driven by the immediate economic gains from exploiting forest resources (Cozma et al., 2023). The power and influence of landowners also complicate the enforcement of conservation laws. The ambiguity in land ownership, particularly with joint ownership systems, can further exacerbate the problem, as unclear ownership rights can lead to conflicts and inadequate forest management (Lawasi, 2024).

The results of this study underscore the complex dynamics driving deforestation in North Sumatra. While industrialization does not significantly contribute to deforestation, population density is crucial in increasing deforestation rates, primarily due to the rising demand for wood, land, and forest products. On the other hand, land ownership does not have a significant impact, mainly due to landowners' non-compliance with conservation regulations and the political and economic influence they wield. These findings provide valuable insights into the factors contributing to deforestation in North Sumatra and

highlight the need for more effective policies that address the root causes, particularly population growth and land use pressures, while also encouraging the adoption of sustainable industrial practices and strengthening the enforcement of land management regulations (Lieke et al., 2023).

The findings of this study provide valuable insights into the key factors influencing low-carbon development in North Sumatra, explicitly focusing on deforestation, energy consumption, land transportation, and industrialization. The statistical significance of these variables, as evidenced by their respective p-values and t-statistics, confirms their critical role in shaping the region's carbon emissions and environmental sustainability. This discussion compares the results with recent studies to highlight similarities and differences, offering a comprehensive understanding of the challenges and opportunities for achieving low-carbon development in the region.

The key factors influencing low-carbon development in North Sumatra, mainly deforestation, energy consumption, land transportation, and industrialization, align with previous research that highlights the complex interplay of these variables in shaping regional carbon emissions. For instance, Androniceanu et al. (2024) emphasize the critical role of renewable energy and policy initiatives in mitigating environmental impacts. This resonates on the importance of local governance and energy consumption patterns (Androniceanu et al., 2024). Additionally, Najicha et al. (2023) have demonstrated that sustainable energy management and reducing deforestation and industrialization are essential for low-carbon transitions. Compared to these global and national-level studies, the unique contribution of this research lies in its localized focus on North Sumatra, revealing how the integration of regional factors such as land transportation and industrialization requires tailored, context-specific solutions to reduce carbon emissions effectively. This study supports the findings of global literature and highlights the regional dynamics that must be considered to achieve low-carbon development.

Deforestation significantly hinders low-carbon development in North Sumatra, with a strong negative relationship between deforestation and the low-carbon development index. The negative coefficient for deforestation highlights how deforestation exacerbates carbon emissions by reducing the number of trees that absorb carbon dioxide. Deforestation is one of the leading causes of climate change, and reducing deforestation is a key strategy to mitigate global warming and promote sustainable low-carbon development. In line with these studies, the results in North Sumatra underline the urgent need for stricter forest protection policies, reforestation efforts, and sustainable land-use practices to reduce the environmental impact of deforestation. Furthermore, addressing illegal logging and encroachment on protected forest areas is essential to reversing the trend of deforestation and improving the region's low-carbon development trajectory.

This approach aligns with Wang et al. (2025), which explores the relationship between renewable energy utilization and circular economy strategies in 30 Chinese provinces from 2000 to 2023. Results show that both strategies significantly reduce CO2 emissions, with renewable energy having a negative association. The circular economy strategy enhances resource efficiency and minimizes waste, demonstrating the effectiveness of China's Circular

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Economy Promotion Law. The study emphasizes the need for region-specific policy measures to achieve environmental sustainability (Wang et al., 2025). It also complements studies like Najicha et al. (2023), emphasizing the importance of sustainable land-use practices and reforestation for mitigating climate change. It reinforces the study's call for more stringent policies to reduce deforestation and promote low-carbon development.

Energy consumption, mainly from fossil fuels, has long been recognized as a significant driver of carbon emissions. The results of this study confirm that increased energy consumption negatively impacts low-carbon development in North Sumatra. Energy consumption from fossil fuels, such as coal and oil, directly contributes to carbon dioxide emissions, exacerbating climate change and hindering low-carbon initiatives. The growing demand for energy-intensive services and products in industrialized economies leads to higher carbon emissions. In the context of North Sumatra, energy consumption, primarily derived from non-renewable sources, remains a significant challenge for achieving low-carbon development. The results indicate the necessity of transitioning to cleaner energy sources, such as solar, wind, and hydropower, to mitigate the carbon emissions associated with energy production. Policies encouraging the adoption of energy-efficient technologies and renewable energy initiatives are critical to reducing the region's carbon footprint of energy consumption.

Najicha et al. (2023) confirm that increased energy consumption, mainly from fossil fuels, significantly hampers low-carbon development in North Sumatra, reinforcing existing literature on the relationship between energy use and carbon emissions. Najicha et al. highlighted how fossil fuel consumption is a major contributor to greenhouse gas emissions, emphasizing the need to shift toward renewable energy sources to mitigate environmental impacts. This study underscores the necessity of transitioning from non-renewable energy sources, such as coal and oil, to cleaner alternatives like solar, wind, and hydropower in North Sumatra. Moreover, Androniceanu et al. (2024) further support this perspective by examining the role of renewable energy adoption and energy-efficient technologies in reducing carbon emissions globally. Their analysis suggests that the shift to renewables is essential for carbon reduction and fostering long-term sustainable development. This study builds upon these previous works by emphasizing the regional importance of energy transition policies in North Sumatra, reinforcing the need for local efforts to promote clean energy initiatives and energy-efficient technologies as part of a broader low-carbon development strategy.

Land transportation has been identified as another significant contributor to carbon emissions in North Sumatra, with the study's results indicating a substantial negative relationship between land transportation and low-carbon development. The coefficient for land transportation underscores the impact of vehicle emissions on the region's carbon output. Transportation is a significant source of carbon emissions, mainly through vehicle exhaust. In North Sumatra, the rapid increase in vehicles and their reliance on fossil fuels has exacerbated the region's carbon footprint. Reducing transportation frequency and improving the transportation system's efficiency are vital strategies for reducing carbon emissions. In this study, the findings support the need for policies that promote public

transportation, encourage the use of electric vehicles (EVs), and improve fuel efficiency standards to decrease the reliance on fossil-fuel-powered vehicles. This shift toward more sustainable transportation options, including expanding the infrastructure for EVs and improving urban mobility systems, could significantly reduce emissions from the transportation sector, facilitating the region's transition toward low-carbon development.

The study on low-carbon development in North Sumatra identified land transportation as a significant barrier to emission reduction efforts (Siregar et al., 2024). This condition aligns with broader Southeast Asian patterns observed in Malaysia, where transport accounts for 28.8% of fossil fuel emissions, and urbanization drives 2.67% long-term CO_2 increases per 1% urban growth (Solaymani, 2022). The North Sumatra findings mirror Malaysia's challenges with energy intensity - where short-term efficiency gains paradoxically increase emissions due to rebound effects in vehicle utilization patterns.

Globally, these transportation-emission dynamics reflect patterns in China's Wuhan metropolitan area, where commuting carbon emissions exhibit nonlinear relationships with urban density and infrastructure development (Guo et al., 2023). However, North Sumatra's agricultural context introduces unique complexities, as expanded road networks facilitate deforestation and mechanized farming practices that compound emissions from transport and land-use changes (Harahap et al., 2023). This dual pressure contrasts with Malaysia's more urban-focused transportation emissions profile. However, both regions show transportation GDP per worker as a key emissions driver (0.57-0.63% emission increases per 1% productivity growth) (Solaymani, 2022).

The study recommends multi-pronged solutions combining Malaysia's successful adoption of compressed natural gas vehicles with China's innovative urban mobility strategies (Guo et al., 2023). For North Sumatra specifically, researchers emphasize electrifying agricultural transport fleets while implementing congestion pricing in Medan's urban core. These targeted approaches address the region's distinct emission drivers while incorporating lessons from international best practices in sustainable transportation planning.

Industrialization has long been associated with increased carbon emissions due to the energy-intensive nature of industrial processes. The results of this study reveal that industrialization in North Sumatra negatively impacts low-carbon development. Industrial activities are a significant source of carbon dioxide emissions. In North Sumatra, the rapid pace of industrialization has been linked to increased demand for fossil energy, particularly in manufacturing and energy-heavy sectors. The negative impact of industrialization on low-carbon development is that industrial waste, greenhouse gas emissions, and outdated, inefficient technologies contribute significantly to environmental degradation. This study's findings suggest that to mitigate the environmental impact of industrialization, North Sumatra must focus on promoting sustainable industrial practices. This condition could include adopting cleaner technologies, improving energy efficiency, and shifting towards green industries. Moreover, carbon pricing mechanisms, such as carbon taxes and emissions trading schemes, could incentivize industries to reduce their carbon emissions and transition towards low-carbon operations.

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The study on industrialization in North Sumatra highlights the negative impact of industrial activities on low-carbon development, indicating that industrialization is a major driver of carbon dioxide emissions due to energy-intensive processes and inefficient technologies. This result aligns with findings from Li et al. (2022), which demonstrated that industrialization generally exacerbates CO_2 emissions, particularly in middle- and low-income countries where outdated technologies and fossil fuel dependency dominate (Ehigiamusoe et al., 2023). Similarly, research in East Africa revealed that industrialization spurred significant increases in CO_2 emissions due to reliance on carbon-intensive industries and inefficient energy utilization models (Yu et al., 2024). However, studies suggest that upgrading industrial structures and adopting cleaner technologies can mitigate these effects. For instance, a study using data from 41 countries found that linking manufacturing with service sectors reduced CO_2 emissions by 0.94 metric tons per capita for every 0.1 unit increase in structural integration (Dong et al., 2020).

These findings collectively emphasize the need for North Sumatra to adopt sustainable industrial practices, such as cleaner technologies, energy efficiency improvements, and green industry transitions. Additionally, implementing carbon pricing mechanisms like taxes or emissions trading schemes could incentivize industries to reduce emissions, mirroring global strategies to balance economic growth with environmental sustainability.

The findings of this study provide several important implications for policymakers in North Sumatra. The significant influence of deforestation, energy consumption, land transportation, and industrialization on low-carbon development highlights the need for an integrated policy approach that addresses these key drivers of carbon emissions. Policies aimed at reducing deforestation, promoting renewable energy, enhancing public transportation, and encouraging green industrial practices are essential to advancing low-carbon development. Specifically, enforcing stricter forest protection laws, promoting reforestation, and encouraging alternative energy sources could mitigate carbon emissions and foster a more sustainable economy. Additionally, incentivizing the adoption of energy-efficient technologies, increasing the use of public transportation, and supporting the transition to electric vehicles would contribute to reducing emissions from energy consumption and transportation. Furthermore, using cleaner technologies and carbon pricing and fostering a green industrial revolution can help North Sumatra reduce its industrial carbon footprint.

The study's findings on low-carbon development in North Sumatra highlight significant influences from deforestation, energy consumption, land transportation, and industrialization, emphasizing the need for integrated policy approaches to address these carbon emission drivers. This result aligns with previous research in Malaysia, which demonstrated that economic growth and deforestation adversely impact carbon emissions, suggesting that afforestation, reforestation, and sustainable forest management are critical to reducing emissions while maintaining economic growth (Begum et al., 2020). Similarly, studies on rainforest conversion in Indonesia have shown that land-use intensification for plantations leads to significant carbon losses and environmental degradation, reinforcing the importance of policies to preserve forest ecosystems and promote sustainable agricultural practices (Guillaume et al., 2018).

The study's emphasis on deforestation as a key factor resonates with findings from spatial-temporal analyses of deforestation hotspots in Sumatra, which identified human activities such as oil palm plantations and wood fiber production as major contributors to forest loss (Singh & Yan, 2021). These insights suggest that stricter forest protection laws and reforestation initiatives could mitigate emissions effectively. Furthermore, promoting renewable energy and green industrial practices aligns with Indonesia's broader low-carbon development models, which advocate multi-sectoral approaches to reduce emissions while fostering sustainable growth. Together, these studies underscore the necessity of coordinated efforts across sectors to achieve low-carbon development goals in North Sumatra.

The article sheds light on the various factors influencing deforestation in North Sumatra and provides important insights into the region's forest resource management dynamics. The analysis reveals that industrialization, population density, and land ownership are key variables that affect deforestation. However, the complexity of these relationships and how different factors can either exacerbate or mitigate the pressures on forests. The discussion will focus on comparing the findings of this study with previous research, particularly recent studies within the last decade, to deepen the understanding of the regional deforestation dynamics and to suggest potential solutions for sustainable forest management.

A notable finding is the lack of a significant impact of industrialization on deforestation. The coefficient for industrialization was found to be statistically insignificant, indicating that, at present, industrialization does not directly contribute to deforestation in North Sumatra. This study contrasts with earlier studies, such as Kinda and Thiombiano (2021), who suggested that industrial economic rent could drive deforestation. However, it is important to consider that, in the context of North Sumatra, industries might have begun adopting more sustainable practices, such as using more efficient technologies, increased recycling efforts, and better waste management practices. These efforts can help reduce the demand for natural resources, including timber, thus mitigating the negative environmental impact associated with industrial growth. This study aligns with the findings of Voumik and Ridwan (2023), who also argued that industrialization's impact on deforestation could be minimized with the right policies and industrial practices. Therefore, while industrialization may have historically contributed to deforestation, the ongoing shift toward more sustainable industry practices may reduce this influence. As the population grows, the expansion of agricultural land, settlements, and the need for fuelwood intensify, driving the encroachment on forested areas. The results from this study align with these findings, underscoring that population density remains a significant factor influencing deforestation in North Sumatra. The increase in the population leads to a higher demand for forest products and exacerbates the competition for land, further accelerating the destruction of forest ecosystems.

However, the finding that land ownership rights do not significantly affect deforestation is more complex and warrants further exploration. In North Sumatra, the situation is different. This study suggest that despite property rights, many landowners do not comply with forest conservation regulations. The economic pressures they face, and their political and economic power make it challenging to enforce conservation laws effectively. Furthermore, joint land ownership can create ambiguities in land management, leading

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to deforestation when ownership rights are not clearly defined. This result is consistent with Liu et al. (2024), who also pointed out that land ownership, when combined with economic pressures and unclear property rights, can often lead to increased deforestation rather than its reduction. This study suggest that more stringent regulations and better enforcement mechanisms are needed to ensure landowners comply with conservation efforts.

In light of these findings, it is clear that a multi-faceted approach is required to tackle deforestation in North Sumatra. While industrialization may not be a significant driver of deforestation, population density continues to exert significant pressure on forest resources. Additionally, land ownership issues must be addressed through improved legal frameworks and more effective enforcement of conservation laws. Moreover, the findings suggest the need for policies that focus on increasing land use efficiency, promoting sustainable agricultural practices, and encouraging reforestation efforts. The private sector, communities, and government must also emphasize fostering sustainable land management practices.

Policies encouraging industrial innovations, such as using renewable resources and cleaner technologies, could further reduce industrialization's impact on deforestation (Raihan, 2023). Compared with other recent studies, it underlines the importance of addressing both direct and indirect drivers of deforestation. While some factors, such as industrialization, may show reduced impacts due to technological advancements, other factors, such as population growth, pose significant challenges. Addressing deforestation requires a comprehensive strategy that includes population control measures, sustainable industrial practices, and robust forest conservation policies. Additionally, the role of local governance and land tenure systems must be strengthened to ensure that conservation regulations are effectively enforced and that landowners have clear incentives to protect forests. By drawing from local experiences and global best practices, developing a more sustainable approach to forest management in North Sumatra and beyond is possible.

CONCLUSION

Achieving low-carbon development in North Sumatra requires a multi-faceted approach that focuses on reducing deforestation, improving energy efficiency, promoting sustainable transportation, and addressing industrial emissions. Local governments play a crucial role in this process by implementing policies to protect forests, regulate land use, and encourage the use of renewable energy. Additionally, efforts to improve public transportation, support low-emission vehicles, and introduce carbon pricing can help reduce carbon emissions from the transportation and industrial sectors.

Preserving forest areas, particularly protected forests, is essential for carbon absorption and maintaining biodiversity. Moreover, managing population density through better urban planning can help reduce pressure on natural resources. North Sumatra can move toward a low-carbon future by enhancing institutional quality, enforcing environmental laws, and fostering public awareness. This condition will require coordinated action from government, industry, and the community, ensuring that development is environmentally sustainable and beneficial for future generations.

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