Export trends and determinants of Malaysia's wood pellets

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Abstract

Malaysia seeks to strengthen its position in the global wood pellet market but remains behind regional leaders such as Vietnam (USD 800 million exports in 2022 vs. Malaysia's USD 126 million). This study analyzes determinants of Malaysia's wood pellet exports from 2012–2023 using OLS models and a 12-year dataset. Key variables include macroeconomic factors (GDP, exchange rate, inflation), market factors (pellet price), production factors (labor), and forest resource endowment, which includes harvested roundwood volume and total forest area, integrated within the Heckscher-Ohlin framework. Export growth is assessed using CAGR and AAGR. Results show GDP and harvested roundwood volume positively influence exports, while higher pellet prices, inflation, and expanding forest area correlate negatively. Despite COVID-19 disruptions, exports grew steadily, with a quarterly CAGR of 37.2% and AAGR of 6%. The study introduces a novel approach by incorporating natural resource endowment into trade theory, offering new insights into resource-driven competitiveness in forest product exports.

Keywords: export trade; wood pellets; determinants; trends

1. Introduction

As the world shifts towards renewable energy sources, wood pellets—a wood-based biofuel made from compressed organic matter or biomass—have seen a surge in global demand [1]. This trend is driven by increasing environmental concerns, international commitments to carbon reduction, and the pursuit of sustainable energy solutions [2]. As a result, the wood pellet industry has become a vital component of Malaysia's renewable energy sector, offering substantial economic opportunities and contributing to the country's export growth. Thus, in recent years, Malaysia has emerged as a significant player in the global wood pellet market, capitalizing on its abundant

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biomass resources and strategic geographical location. In 2023, Malaysia was the eighth largest exporter of wood pellets worldwide [3].

Malaysia's wood pellet industry has experienced substantial growth, supported by favorable government policies such as the National Biomass Action Plan 2023-2030 (NBAP), advances in production technology, and increased investments [4]. The government's commitment to promoting renewable energy, coupled with incentives and subsidies, has created a conducive environment for the industry's expansion. Furthermore, advancements in production technology have improved the quality and competitiveness of Malaysian wood pellets, making them more attractive to international markets. Increasing investments in the sector have also played a crucial role in scaling up production capacity and improving supply chain efficiency [5].

Despite Malaysia's abundant biomass resources and established wood-based industries, its wood pellet export volumes lag significantly behind those of the regional leader, Vietnam. Vietnam achieved an estimated USD 500 million in wood pellet exports in 2023, while Malaysia's exports were approximately USD 120 million during the same period, 75% behind [6]. Vietnam dominates the regional wood pellet market with an installed production capacity of about 3.5 million tons per year, compared to Malaysia's estimated 130,000 tons per year. In 2024, Vietnam exported 6.03 million tons of pellets, earning USD 805 million, while Malaysia shipped 1.13 million tons valued at USD 126 million [58]. Export prices also differ slightly: Vietnam averaged USD 132.6 per ton (USD 146.3 for Japan and USD 104.3 for Korea), whereas Malaysia averaged USD 127 per ton, with Japan paying up to USD 137 per ton [59]. Both countries produce pellets with similar energy content, typically 17–19 GJ per ton; however, Vietnam's scale and market penetration far exceed Malaysia's, underscoring a significant competitive gap [60,61].

This disparity raises concerns about Malaysia's ability to fully capitalize on the growing global demand for renewable energy sources, such as wood pellets. Factors such as inconsistent policy support, limited investment in advanced production technologies, and inadequate supply chain infrastructure can inhibit export potential [7]. In contrast, Vietnam has effectively used government incentives and strong foreign direct investment to scale up production and secure major export markets [8]. Addressing these challenges is crucial for Malaysia to improve its competitiveness and establish a stronger presence in the international trade of wood pellets.

This study provides a detailed analysis of Malaysia's wood pellet export performance over a 12-year period (2012–2023), integrating economic and environmental variables. Existing research on wood pellet markets in Vietnam, Japan, Korea, and the EU has primarily examined production trends, policy impacts, and isolated market dynamics, such as price fluctuations and supply chain bottlenecks. In Japan, research underscores the role of feed-in tariff (FIT) programs and sustainability certification requirements in shaping import demand, which is projected to more than double by 2025. However, policy changes and certification challenges introduce uncertainty in long-term trade flows [62]. Similarly, South Korea's recent decision to phase out biomass subsidies signals structural changes in regional trade dynamics, but few studies quantify the econometric impact of such policy reforms on export performance [63]. European-focused studies primarily address market growth, price volatility, and supply chain sustainability, but they often overlook the integration of natural resource endowment variables, such as forest area and harvested roundwood volume, into econometric models of trade determinants [64]. Econometric analyzes often emphasize trade policies and demand-side factors, but they rarely integrate natural resource endowment variables, such as harvested roundwood volume and forest area, into models of export performance. This narrow focus leaves a gap in understanding how resource availability interacts with macroeconomic and market factors to influence competitiveness in emerging exporters like Malaysia.

To address this gap, this study is guided by two key research questions: 1. How do natu-

ral resource endowments, specifically forest area and harvested roundwood volume, influence Malaysia's wood pellet export performance from 2012 to 2023? 2. What macroeconomic and forest resource factors significantly influence Malaysia's wood pellet exports? 3. Can forest area and roundwood harvest be effectively integrated into econometric models to predict future export trends and identify strategic growth opportunities for Malaysia's wood pellet industry?

The findings of this research are particularly novel in bridging economic theory with sector-specific reality, specifically in the forestry-based wood pellet sector, where global competitiveness is influenced by both resource availability and market focus. This approach is particularly suited to understanding emerging trade patterns by balancing economic growth with sustainable resource management. Analysis of forest endowments, such as forest area and harvested roundwood as critical determinants, highlights environmental constraints and opportunities within the industry's expansion [9]. These insights aim to bridge gaps in the existing literature and provide actionable recommendations for policymakers and industry stakeholders.

The subsequent sections of this paper detail the methods used to analyze export trends and determinants, followed by a discussion of the results and their implications. Ultimately, the findings aim to inform strategies for sustainable growth and long-term success in Malaysia's wood pellet industry.

2. Literature Review

The theoretical foundation for this study of Malaysia's wood pellet export trends and determinants is rooted in established economic and trade theories. These theories provide a framework for understanding the complex interactions between resource endowments, macroeconomic conditions, and international trade performance. The following theoretical perspectives underpin the conceptual framework and methodological approach of the study.

i) Heckscher-Ohlin Theory of Comparative Advantage: Countries tend to export goods that utilize their abundant resources efficiently and import goods that use their scarce resources. Malaysia's forest endowment, including the volume of roundwood harvested and the total forest area, provides a comparative advantage in producing wood pellets. The theory justifies examining forest-related variables as significant determinants of export trends, apart from the land, labor, and capital factors. An adaptation of the theory, specifically the Heckscher-Ohlin-Vanek (HOV) model, builds on this by examining how much of these resources are used in the products a country exports. For Malaysia, which has abundant forests and labor, this means it naturally exports wood pellets—a product that requires a lot of land and workers. This theory helps to show why Malaysia focuses on using its forest resources and workforce to grow its wood pellet exports sustainably [9,10].

ii) Resource-Based View (RBV): The Resource-Based View is a strategic theory that emphasizes the role of internal resources in gaining and sustaining a competitive advantage. According to the RBV, organizations or countries that possess valuable, rare, inimitable, and non-substitutable (VRIN) resources are better positioned to outperform their competitors. These resources can be tangible, such as natural assets like forests and infrastructure, or intangible, including technical knowledge, certifications, and institutional capacity. In the context of Malaysia's wood pellet industry, RBV helps explain how factors such as forest endowment, sustainable management practices, and compliance with international standards can serve as strategic assets that drive export performance. Using these unique resources and capabilities effectively, the industry can improve its position in global bioenergy markets [11].

iii) Price Elasticity of Demand in International Trade: The responsiveness of export volume to changes in product price impacts competitiveness in global markets. Wood pellet prices and global

demand fluctuations directly influence Malaysia's ability to compete, especially against major players such as Vietnam and North America. High product prices may discourage international buyers, while low prices can increase demand but reduce profit margins [10].

iv) Keynesian Economic Growth Model: Economic growth measured by GDP stimulates export performance by increasing production capacity, technological investment, and global competitiveness. GDP acts as a macroeconomic indicator that reflects overall economic activity, linking it to the export capacity of wood pellets. Growth in GDP may indicate better infrastructure, policy support, and production efficiencies benefiting export trends [12].

v) Global Trade Dynamics and Market Access: Trade barriers, currency exchange rates, and inflation impact a country's export performance. Fluctuations in exchange rates and inflation rates can affect Malaysia's trade competitiveness and the purchasing power of importing countries. Policies such as subsidies, certifications, and market access agreements influence Malaysia's positioning in global markets [13].

For a study of wood pellet exports, the conceptual framework shows how macroeconomic variables (GDP, inflation, and exchange rates), market-related factors (wood pellet price), endowment of natural resources (forest area and harvested volume), and trade-related factors (exchange rates) influence the export volume of wood pellets. The framework is grounded in the Heckscher-Ohlin theory and the resource-based view, which highlight the importance of resource availability and economic conditions in shaping trade outcomes [14]. These theories collectively support the hypothesis that resource endowments, macroeconomic conditions, and market competitiveness jointly influence Malaysia's wood pellet export trends. The following framework examines how macroeconomic, resource-based, and trade-related factors drive export outcomes.

2.1. Macroeconomic factors

Macroeconomic factors are the broad economic conditions and trends that influence the performance, stability, and growth of national and global economies. These factors encompass key indicators such as inflation, interest rates, gross domestic product (GDP), employment levels, exchange rates, and fiscal and monetary policies. Understanding macroeconomic dynamics is essential for policymakers, businesses, and investors, as it shapes strategic decisions, impacts market behavior, and determines the overall economic climate. This section provides an overview of the principal macroeconomic forces and their implications for economic development, financial planning, and long-term sustainability [67].

Gross Domestic Product (GDP) represents the total monetary value of all goods and services produced within a country's borders in each period. As an independent variable, GDP serves as a key indicator of a nation's economic capacity and production potential. Higher GDP typically enables greater export volumes by providing the industrial base and resources needed for international trade. For forest product exports specifically, GDP growth often correlates with increased processing capacity and infrastructure development that facilitates timber harvesting and manufacturing. Countries with robust GDP tend to have more advanced value-added wood processing industries, allowing them to export higher-value forest products rather than just raw materials [15–17].

Exchange rates measure the value of a domestic currency relative to foreign currencies and significantly impact export competitiveness. For forest product exporters, currency depreciation can provide immediate price advantages in international markets, making products cheaper for foreign buyers. However, the benefits may be offset if production relies on imported equipment or chemicals priced in stronger currencies. Exchange rate volatility poses challenges for forest industries because many wood products are traded in U.S. dollars under long-term supply

contracts. A strong domestic currency can make exports less competitive but may lower the cost of importing advanced processing technology. The impact of the exchange rate varies across product categories: primary products such as logs are more sensitive to currency fluctuations than differentiated products such as designer furniture, where quality and brand reputation may outweigh price considerations [15–17,50].

Inflation measured through indices like the Consumer Price Index (CPI) or Producer Price Index (PPI), reflects the rate at which general price levels rise within an economy. For export-oriented forest industries, inflation impacts production costs throughout the supply chain—from raw timber extraction to final product manufacturing. High inflation can erode profit margins by increasing expenses for labor, equipment, transportation, and energy without corresponding increases in international product prices. This is particularly challenging for forest product exporters because many wood products compete in price-sensitive commodity markets. Additionally, inflation may lead to currency depreciation, which could paradoxically make exports more price-competitive abroad while squeezing domestic producers between rising input costs and fixed export prices [15,16,49,50].

2.2. Resource factors

In assessing the export performance of forest products, resource factors play an essential role in shaping both the capacity and sustainability of production. Among these, the volume of roundwood harvested and the total forest area stand out as critical indicators of the availability and management practices of forest resources in a country. The volume of roundwood harvested reflects the intensity of forest utilization and the operational scale of wood production, while the total forest area provides insight into the long-term sustainability and ecological potential of forest-based economic activities.

Globally, nearly 1.9 billion cubic meters of industrial roundwood are harvested annually, with the United States, Russia, China, Canada, and Brazil among the top producers. This harvested volume directly supports the production of exportable goods such as sawn wood, wood pellets, and paper products. For the southern United States, increased roundwood consumption by wood pellet mills contributed to a 180% growth in pellet exports between 2012 and 2017 [53]. Meanwhile, Malaysia's total forested area of approximately 22.2 million hectares, which accounts for more than 60% of the national land area, provides a substantial base for biomass sourcing [54]. Within this forest estate, permanent forest reserves contribute significantly to the sustainable supply of roundwood, wood chips, and sawdust, which are key materials for pellet manufacturing.

The extent of the forest area also plays a vital role in the development of export potential. Countries with larger forest areas tend to have more diversified forest product outputs and greater resilience in maintaining export levels amid environmental and market fluctuations. These findings underscore the relevance of forest-based variables in explaining export dynamics, but such variables remain underutilized in Southeast Asian biomass trade models. By integrating forest area and roundwood harvest into the analysis, this study addresses a critical gap and aligns with international precedents that link resource availability to export competitiveness. The inclusion of the volume of harvested roundwood and the total forest area as key independent variables reflects how the endowment of forest resources affects the export performance of Malaysia under the Heckscher-Ohlin framework, where abundant natural resources drive a comparative advantage in biomass-based trade. Understanding the interplay between these resource factors and export performance is essential for policymakers and industry stakeholders to balance economic growth with sustainable forest management.

Harvested roundwood volume: Forest resources are a cornerstone of Malaysia's natural

endowment, providing renewable and sustainable raw materials for the wood-based industry. Within the forest estate, permanent forest reserves ensure a consistent supply of roundwood, wood chips, and sawdust, which are key inputs for pellet manufacturing and other downstream industries. Harvested roundwood volume is not only a measure of forest utilization but also a critical factor that underpins Malaysia's comparative advantage in forest product exports. The annual volume of harvested roundwood determines the availability of raw materials for both primary and secondary wood product manufacturing, influencing the country's ability to compete in global markets.

The intrinsic qualities of roundwood such as density, moisture content, lignin composition, and calorific value—affect pellet efficiency and market competitiveness. Hardwoods like Acacia mangium and Shorea species offer high energy density and low ash content, making them highly desirable in export markets that demand consistent combustion quality. Countries with abundant roundwood production, such as Malaysia, can leverage this resource endowment to develop export-oriented forest industries, provided sustainable yield management practices are maintained to ensure long-term competitiveness [9,18,19].

Total forest area indicates the potential for future wood supply and is often associated with environmental regulations that may limit harvesting. Nations with large, well-managed forest resources typically enjoy comparative advantages in wood product exports; however, this depends on factors like species quality, accessibility, and processing infrastructure. Malaysia's total land area is approximately 33 million hectares, of which about 20.06 million hectares, or roughly 61%, is covered by forests. This includes 5.97 million hectares in Peninsular Malaysia, 4.25 million hectares in Sabah, and 9.84 million hectares in Sarawak [57]. The total forest area indicates the potential for future wood supply and is often associated with environmental regulations that can limit harvesting. Nations with large, well-managed forest resources typically enjoy comparative advantages in wood product exports; however, this depends on factors such as species quality, accessibility, and processing infrastructure. The composition of forest endowment, whether dominated by natural forests or plantations, also affects the types and quality of exportable products [9,18,19].

2.3. Market factor

Market factors encompass both external and internal conditions that shape pricing behavior and competitiveness in the international wood pellet trade. These factors include global energy demand trends, trade policies, consumer preferences for renewable energy, and technological advancements in biomass utilization. When global markets shift toward cleaner and more sustainable energy sources, the demand for wood pellets typically rises, driving increased production and export activities. Among these factors, the wood pellet price serves as a key market indicator, reflecting production costs and demand conditions. Higher fossil fuel prices make wood pellets a more attractive alternative, boosting demand and export prices. Conversely, when fossil fuel prices decline, wood pellet prices tend to fall due to reduced competitiveness [56].

Product price represents the market value of exported forest products, such as sawn wood, wood pulp, and paper. This variable plays a critical role in determining export competitiveness in global markets. When domestic prices rise relative to international competitors, export demand may decline unless offset by superior quality or unique product characteristics. For primary products like roundwood, prices are highly sensitive to fluctuations in the global commodity market. Processed wood products generally command higher prices but face stronger competition from alternative materials. Pricing dynamics are particularly important for forest products because they compete not only with other wood-based goods but also with substitutes such as plastics,

metals, and concrete in various applications [20,48].

2.4. Production factor

Production factors refer to the essential inputs that determine the efficiency, cost structure, and overall productivity of the wood pellet industry. These include the availability of skilled labor, the adoption of advanced technologies, production capacity, and access to high-quality raw materials. A well-trained workforce ensures smooth operations, consistent quality control, and effective handling of modern processing equipment, while technological innovations improve energy efficiency and minimize production waste. Additionally, factors such as plant location, logistics, and supporting infrastructure significantly influence production scale and operational efficiency. Collectively, these elements shape a country's ability to meet export demand, maintain global competitiveness, and achieve sustainable growth in the biomass market [21].

Labor force refers to the pool of available workers engaged in economic production. In wood pellet exports, labor plays a dual role; it enables production through workforce availability and affects competitiveness through skill levels and costs. A sufficient, skilled labor force allows countries to efficiently convert raw materials into export-ready pellets while meeting international quality standards. Labor costs influence final product pricing, creating trade-offs between production scale and cost competitiveness. The sector particularly relies on workers with technical skills for pellet mill operation, quality control, and logistics management. Labor productivity ultimately determines how effectively a country can transform its forest resources into exportable pellets, making workforce development a key factor alongside natural resource endowment in the global wood pellet trade [21,22].

The conceptual framework in Figure 1 illustrates the relationship between various macroeconomic and resource factors and the export performance of wood pellets. The dependent variable, wood pellet export, is influenced by the four main categories of independent variables. Macroeconomic factors such as GDP, inflation, and exchange rates affect the country's production capacity, competitiveness, and trade environment. Resource endowment variables, including harvested roundwood volume and total forest area, reflect the availability and sustainability of raw materials essential for wood pellet production. Additionally, the price of wood pellets represents a market-driven factor, and the production-based labor force directly influences global demand and export revenue. Together, these variables form an integrated framework to assess the determinants of export trends in the wood pellet sector.

3. Materials And Methods

The inclusion of forest area and harvested roundwood volume as explanatory variables in this study is grounded in both theoretical relevance and empirical precedent. These indicators reflect the availability and active utilization of biomass resources, which are essential inputs in wood pellet production. Empirical studies have shown that forest cover positively correlates with the volume and diversity of forest product exports, especially in regions such as the EU and BRICS nations [55]. Brandeis and Abt (2019) found that in the southern United States, wood pellet exports grew by approximately 180% between 2012 and 2017, closely linked to increased roundwood consumption by pellet mills, which accounted for 27% of all industrial fuelwood output during that period [65]. Similarly, Koebel et al. (2015) extended the Heckscher-Ohlin-Vanek framework to include forest resource endowment and showed that forest area significantly influenced net trade performance in the pulp, paper, and furniture sectors across European countries [66]. However, such variables remain underexplored in Southeast Asian contexts, particularly in Malaysia. By

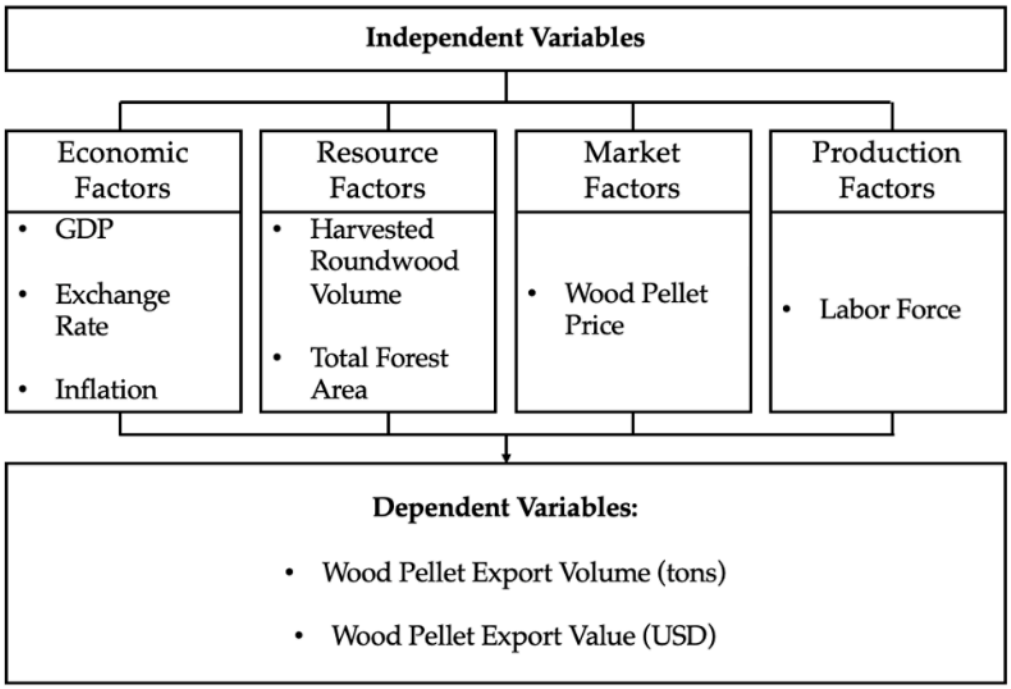

Figure 1: *Conceptual framework*

integrating these forest-based metrics, this study addresses a critical gap in the literature and offers a more comprehensive understanding of the determinants shaping Malaysia's wood pellet export performance.

3.1. Data collection

Data on wood pellet export value and price from Malaysia was gathered from FAOSTAT by the Food and Agriculture Organization of the United Nations (FAO) [23] and UN COMTRADE (United Nations Commodity Trade Statistics Database) by the United Nations Statistics Division for the period 2012-2023 [24]. Macroeconomic data, such as the inflation rate, labor force, and GDP, were obtained from the World Development Indicators (WDI) database by the World Bank [25]. However, data collected from FAOSTAT and UN Comtrade may be subject to several potential biases. Reporting bias can occur when countries inaccurately report or fail to report trade data, leading to discrepancies between exporters and importers' records. Apart from that, classification bias may arise when products like wood pellets are misclassified under broader categories, reducing the precision of data analysis. Temporal bias may also affect accuracy, as there is often a delay in reporting, and recent data might be estimated rather than actual. Finally, valuation bias can occur due to differences in how countries record the value of goods, such as FOB (free on board) and CIF (cost, insurance, freight), resulting in inconsistent trade figures [26]. Meanwhile, the forest endowment data, such as the volume of harvested roundwood and forest area, were gathered from a more stable forestry statistic based on Malaysia's Forestry Department of Peninsular Malaysia [27], Sabah Forestry Department [28], and the Forest Department of Sarawak [29].

3.2. Export trend and growth analysis

Global trade dynamics are increasingly shaped by the demand for sustainable and high-value commodities, such as wood pellets, which have seen significant export growth due to renewable energy policies such as the EU RED II [European Union, 2018]. Analyzing export trends requires robust metrics like Absolute Growth Rate (AGR) and Compound Annual Growth Rate (CAGR), which quantify short-term fluctuations and long-term trajectories [30]. The export trend uses time series data comprising the export volume of wood pellets from Malaysia from 2012 to 2023, covering a period of 12 years [23]. The trend shows the value and volume of wood pellets year by year, based on the quarterly data from the preceding period. The data were first analyzed and sorted using the annual growth rate (AGR), following Eq. 1:

$$\mathrm{AGR}_t = \frac{Y_t - Y_{t-1}}{Y_{t-1}} \tag{1}$$

Where:
AGR_t = Annual growth rate at year t
Y_t = Total wood pellet export value from Malaysia at year t
Y_{t-1} = Total wood pellet export value from Malaysia at year $t-1$

Export growth analysis was measured based on the average increase in exports or the compound annual growth rate (CAGR), following Eq. 2:

$$\mathrm{CAGR}(t_0, t_n) = \left(\frac{Y(t_n)}{Y(t_0)}\right)^{\frac{1}{t_n - t_0}} - 1 \tag{2}$$

Where:
$\mathrm{CAGR}(t_0, t_n)$ = Compound Annual Growth Rate between year t_0 and t_n
t_0 = Initial year
t_n = Final year
$t_n - t_0 = n$ (Total number of years)
$Y(t_0)$ = Total wood pellet export value from Malaysia at year t_0
$Y(t_n)$ = Total wood pellet export value from Malaysia at year t_n

Meanwhile, the average annual growth rate (AAGR) using the log-linear regression analysis was also estimated following the function (Eq. 3) below:

$$Y = \alpha + \beta X + \varepsilon \tag{3}$$

Where:
Y = $\ln(\mathrm{EXP})$, or the natural logarithm of the export value
α = Constant
β = Coefficient
X = Time
ε = Error term

3.3. Export determinants

Variables based on the macroeconomic variants were investigated as determinants for the export performance, which includes the GDP, product price, exchange rate, and inflation. However,

following the Heckscher-Ohlin theory of factor endowment, two extra variables were added based on the forest endowment, which includes the volume of harvested roundwood and forest area. In this research, double log form approach is considered for estimating robust and elastic results [31]. The following function (Eq. 4) for further estimation procedure was followed:

$$\ln(\text{EXP}) = \alpha + \beta_1 \ln(\text{GDP}) + \beta_2 \ln(\text{LF}) + \beta_3 \ln(\text{ER}) + \beta_4 \ln(\text{P}) + \beta_5 \ln(\text{INF}) + \beta_6 V + \beta_7 A + \varepsilon \quad (4)$$

Where:
EXP = Wood Pellet Export
α = Constant
β = Coefficient
GDP = Gross Domestic Product
LF = Labor Force
EX = Exchange Rate
P = Product Price
INF = Inflation
V = Volume of Harvested Roundwood
A = Forest Area
ε = Error term

Note: All variables use the natural log form except for forest area (A), roundwood volume (V), and inflation (INF), which are expressed in a form that allows their coefficients to be interpreted as elasticities.

3.4. Results estimation method

The model is estimated using Ordinary Least Squares (OLS), a widely used technique for fitting a linear relationship between dependent and independent variables by minimizing the sum of squared errors. OLS is preferred for its unbiased and efficient properties under classical assumptions. To ensure the reliability of results, diagnostic tests for multicollinearity, normality, and autocorrelation are conducted [30]. Multicollinearity inflates standard errors, making it difficult to isolate variable effects; non-normal residuals affect the validity of statistical tests; and autocorrelation in time series data leads to inefficient estimates. Verifying these assumptions is essential for producing robust and credible regression outcomes [32].

3.4.1 Testing for data normality

Data normality refers to whether the distribution of values in a dataset follows a bell-shaped Gaussian curve, in which most data points cluster around the mean. Assessing normality is important for valid statistical inference in regression analysis. Common methods include the Q-Q plot, which visually compares data to a normal distribution—points aligning along the diagonal suggest normality—and the Shapiro-Wilk test, which formally tests the null hypothesis that the data are normally distributed. A Shapiro-Wilk test statistic close to 1 indicates a strong fit to a normal distribution [30].

3.4.2 Testing for autocorrelation

Autocorrelation occurs when the residuals in a regression model are correlated over time, violating the OLS assumption of independent errors. This issue is common in time-series or panel data and

can lead to inefficient estimates and misleading significance tests. The Durbin-Watson (DW) test is used to detect autocorrelation, with values ranging from 0 to 4. A DW value near 2 indicates no autocorrelation; values closer to 0 suggest positive autocorrelation, while values near 4 indicate negative autocorrelation. Typically, a p-value below 0.05 signals significant autocorrelation [32,33].

3.4.3 Testing for multicollinearity

Multicollinearity occurs when independent variables in a regression model are highly correlated, making it difficult to isolate their individual effects. The Variance Inflation Factor (VIF) is commonly used to detect multicollinearity; VIF values below 10 generally indicate no serious issues. Additionally, the correlation coefficient (r) measures the strength and direction of the relationship between two variables, ranging from -1 (perfect negative correlation) to +1 (perfect positive correlation), with 0 indicating no linear relationship [32].

3.4.4 Remedial actions

In regression analysis, violations of OLS assumptions can lead to biased or inefficient estimates, requiring corrective measures. Multicollinearity, where predictors are highly correlated, inflates standard errors and obscures individual effects; remedies include removing variables, combining predictors, or using techniques such as PCA or ridge regression. Heteroscedasticity, or unequal residual variance, affects efficiency and hypothesis testing; solutions include log transformations, Weighted Least Squares, or robust standard errors (e.g., White's correction). Autocorrelation, common in time-series data, biases standard errors; adjustments include adding lagged variables, Cochrane-Orcutt, GLS, or Newey-West standard errors. When residuals deviate from normality, remedies include data transformation, larger samples, or non-parametric methods such as bootstrapping. Selecting the appropriate fix depends on the diagnosed issue and data structure [30,34,35].

4. Results and Discussion

4.1. Export trend and growth analysis

The export value of wood pellets from Malaysia from 2012 to 2023 experienced a fairly increasing but fluctuating trend, as shown in Figure 2 based on quarterly data. Meanwhile, Figure 3 shows the quarterly value and volume of exports cumulatively, comparing the annual cumulative export value and volume for Malaysian wood pellets from 2012 to 2023 [24]. A cumulative total of 708 million US dollars' worth of wood pellets had been exported during the period. The export trend shows a steady increase in value and volume, with a notable decrease in 2015 and from 2019 to 2021. CAGR was estimated at 37.2% (Table 1) with an AAGR of 6% annually (F=178.15, P= 0.0000).

The journey of Malaysia's wood pellet industry began in the early 2010s, during a period when global demand for renewable energy was on the rise. European countries, particularly the UK, Denmark, and Italy, were early adopters of wood pellets as part of their renewable energy policies aimed at reducing carbon emissions following [36]. Recognizing the opportunity, Malaysia began to establish itself as a wood pellet exporter, leveraging its rich forest resources and agricultural residues, such as palm oil waste, to produce wood pellets, as initiated by the 9th Malaysia Plan, which continued with the development of renewable energy policies, such as the National Biofuel Policy in 2006 [37]. During the initial phase, the growth in wood pellet exports from Malaysia was steady but modest. The country's producers focused on building production capacity and establishing connections with key markets in Europe. The relatively small scale of operations

Table 1: *Estimated annual growth, CAGR and AAGR of wood pellet export value (USD mil.)*

Quarter / Year	Export Value (USD Mil.)	Quarter Annual Growth Rate (%)
Q1 2012	818	
Q2 2012	1266	0.55
Q3 2012	1363	0.08
Q4 2012	1493	0.10
Q1 2013	3778	1.53
Q2 2013	2619	-0.31
Q3 2013	2988	0.14
Q4 2013	4827	0.62
Q1 2014	4610	-0.04
Q2 2014	8067	0.75
Q3 2014	7642	-0.05
Q4 2014	7296	-0.05
Q1 2015	4660	-0.36
Q2 2015	5261	0.13
Q3 2015	4511	-0.14
Q4 2015	5943	0.32
Q1 2016	6790	0.14
Q2 2016	6432	-0.05
Q3 2016	6363	-0.01
Q4 2016	9926	0.56
Q1 2017	11094	0.12
Q2 2017	11849	0.07
Q3 2017	16255	0.37
Q4 2017	18663	0.15
Q1 2018	19222	0.03
Q2 2018	21961	0.14
Q3 2018	26811	0.22
Q4 2018	27373	0.02
Q1 2019	18959	-0.31
Q2 2019	19846	0.05
Q3 2019	18885	-0.05
Q4 2019	19913	0.05
Q1 2020	22074	0.11
Q2 2020	9209	-0.58
Q3 2020	19332	1.10
Q4 2020	17544	-0.09
Q1 2021	17876	0.02
Q2 2021	17021	-0.05
Q3 2021	10600	-0.38
Q4 2021	19628	0.85
Q1 2022	26341	0.34
Q2 2022	28932	0.10
Q3 2022	29549	0.02
Q4 2022	41334	0.40
Q1 2023	30305	-0.27
Q2 2023	30234	0.00
Q3 2023	24437	-0.19
Q4 2023	36306	0.49
CAGR		37.2%
	R^2	0.795
AAGR	Coefficient (B)	0.06^{**} (0.005)
	%growth	6%

*Note: Figure in parenthesis indicates standard error of the respective coefficient. ** Significant at the 0.01 level.*

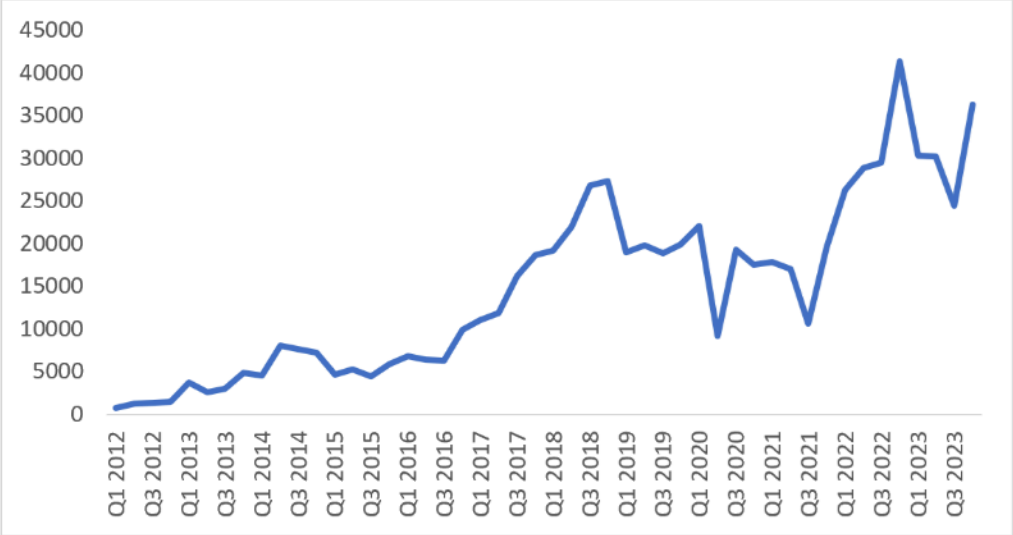

Figure 2: *Quarterly wood pellet export value trend from 2012 to 2023. Source: FAOSTAT (2024)*

and limited market reach kept export volumes moderate. However, the foundational work done during this period set the stage for more significant growth in the subsequent years.

The period from 2016 to 2019 marked a phase of rapid expansion for Malaysia's wood pellet exports with the evolution of the National Biomass Strategy 2020 (NBS 2.0) [38]. Several factors contributed to this growth. First, investments in production technology and capacity have allowed Malaysian producers to increase their output significantly. This expansion in production capacity enabled the country to meet the rising global demand for wood pellets, particularly as more countries began to incorporate biomass energy into their energy mix. One of the most significant developments during this period was Malaysia's successful entry into the East Asian markets, especially South Korea and Japan, in which schemes like the Green Technology Financing Scheme (GTFS) facilitate access to financing for biomass-related businesses in large-scale production [39]. Both countries were looking to diversify their energy sources and reduce their reliance on fossil fuels. Biomass energy, with wood pellets as a key component, has become an attractive option. Malaysian exporters capitalized on this demand by expanding their market reach beyond Europe to include these rapidly growing Asian markets.

By the beginning of the new decade (2020), the wood pellet export market in Malaysia had entered a phase of stabilization and maturation. The rapid growth experienced in the previous year's gave way to a more stable and consistent export pattern. The industry had reached a level of maturity, with established production capacities, well-developed supply chains, and diversified markets. Countries such as Estonia and Denmark, with substantial forest endowments, also show similar patterns in emerging as some of the top exporters of wood pellets in the world [24]. However, the years 2019 to 2021 showed another period of lower export activity for wood pellets from Malaysia due to the covid-19 pandemic. The COVID-19 pandemic has had a profound impact on economic activities worldwide, leading to significant disruptions across various sectors and regions. To contain the spread of the virus, governments implemented lockdowns, travel restrictions, and social distancing measures [40]. These measures resulted in the closure of businesses, schools, and public spaces, leading to a sharp decline in economic activities in sectors such as retail, hospitality, and entertainment. Global supply chains were disrupted

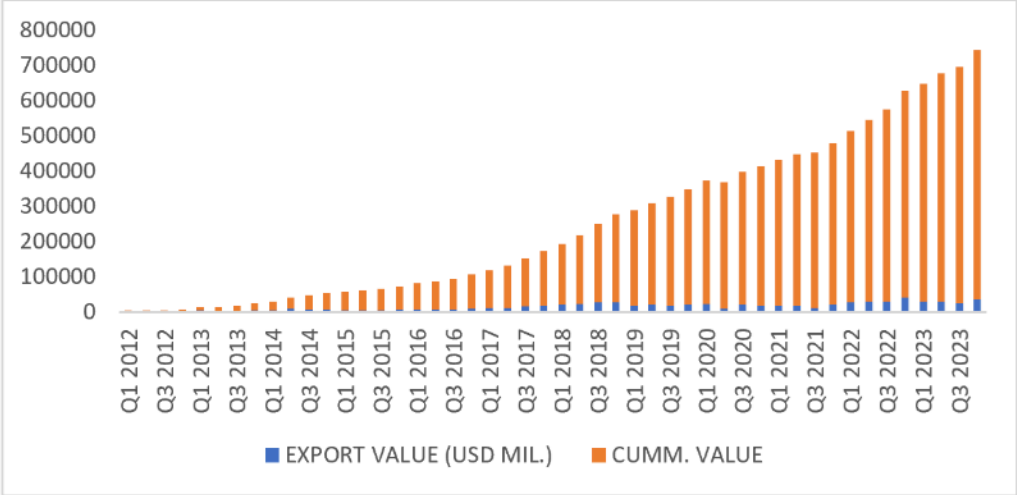

Figure 3: *Annual and cumulative wood pellet export value (USD Mil.) from 2012 to 2023. Source: FAOSTAT (2024)*

due to factory closures, transportation restrictions, and labor shortages. This led to delays in the production and distribution of goods, affecting industries reliant on imported components or raw materials. The economic impact of COVID-19 varied across sectors and regions, with some industries experiencing rapid recovery while others continued to face challenges. The pace of recovery depended on factors such as the severity of the pandemic, government policy responses, and the resilience of local economies [41,42].

4.2. Export determinants

The initial regression, which includes variables such as GDP, product price, exchange rate, inflation, and forest endowments—represented by the volume of harvested roundwood and forest area—shows signs of multicollinearity based on the VIF in Table 2, which contains values higher than 10. Upon further testing, the correlation coefficient analysis presented in Table 3 shows a critical collinearity problem among multiple variables, especially for the exchange rate and labor force.

Upon identification for multicollinearity problem in the initial regression, the remedial action taken to address the problem. The initial analysis revealed multicollinearity among variables, particularly the labor force and exchange rate, with VIF values exceeding acceptable thresholds. Based on Table 3, both both labor force and exchange rate have high collinearity with GDP, with the former also being linear with the volume of harvested roundwood. Thus, actions of omitting the correlated variable were taken to remedy the model. While this resolved multicollinearity, it also raises concerns about losing potentially significant determinants. In certain studies, the roles of the labor force may positively affect export performance, particularly the correlation between labor productivity and the volume of food industry exports across EU Member States for the years 2013, 2016, and 2019 [43]. Similarly, the volatility of the exchange rate may show negative impacts on export performance, as demonstrated by the case study from Malaysia, where currency fluctuations reduce both both volumes and revenues of Malaysian exports [44].

After the re-estimation of the model in Table 4, the regression analysis revealed a positive relationship between the export volume trend and GDP, where the results indicate a significant positive relationship between GDP and wood pellet exports ($p = 0.006$). Higher GDP usually

Table 2: *Regression model parameters for wood pellet exports*

Variable	Estimate	Standard Error	P-value	VIF
Constant	-2136.7518	1771.7258	0.314	
Gross Domestic Product	-0.5072	4.8088	0.923	21.12
Labor Force	140.8100	119.5424	0.324	3795.03
Exchange Rate	1.4595	3.8992	0.733	12.73
Product Price	1.5170	1.3470	0.342	3.15
Inflation	0.1862	0.2247	0.468	4.91
Forest Area	-0.2125	0.2967	0.526	8.82
Volume of Harvested Roundwood	-8.3837	7.5721	0.349	3712.41

Residual standard error = 0.4528 on 3 degrees of freedom; Multiple R-squared = 0.9346; Adjusted R-squared = 0.7819; F-statistic = 6.122 on 7 and 3 DF; p-value = 0.0823

reflects a growing economy with expanded industrial and agricultural output. This surplus production often leads to more goods and services being available for export. As GDP grows, countries typically invest more in infrastructure, technology, and workforce development, all of which enhance export efficiency and competitiveness. Similar findings are reported where GDP was positively associated with biofuel exports in developing countries such as the Philippines and Pakistan through the increase of total production, thus increasing export [45]. This relationship underscores the importance of maintaining robust economic policies to support the renewable energy sector, including wood pellet production.

The higher harvested roundwood volume also shows a positive relationship with the export volume capacity, where the increased magnitude of resources allows a higher export proportion. The positive relationship between harvested roundwood volume and export volume can be effectively explained using the Heckscher-Ohlin theory of international trade. According to this theory, countries tend to export goods that intensively use their abundant and relatively cheaper factors of production [46]. In the context of Malaysia or other forest-rich developing countries, forest resources, specifically roundwood, represent an abundant natural factor endowment.

Table 3: *Correlation coefficient analysis for multicollinearity*

	ln_gdp	ln_lf	ln_er	ln_p	inf	area	vol
ln_gdp	1.00	0.97	0.89	-0.31	-0.08	-0.55	0.96
ln_lf	0.97	1.00	0.88	-0.30	-0.16	-0.63	0.99
ln_er	0.89	0.88	1.00	-0.58	-0.08	-0.40	0.87
ln_p	-0.31	-0.30	-0.58	1.00	0.31	0.06	-0.27
inf	-0.08	-0.16	-0.08	0.31	1.00	0.24	-0.13
area	-0.55	-0.63	-0.40	0.06	0.24	1.00	-0.65
vol	0.96	0.99	0.87	-0.27	-0.13	-0.65	1.00

Therefore, in line with the H-O theory, these countries are naturally positioned to specialize in and export forest-based products, such as wood pellets, timber, and other wood derivatives. However, following the same theory, the declining forest area in Malaysia creates a negative relationship between forest area and export performance in the wood pellet sector. As forest area decreases, the ability to produce and export wood pellets efficiently also declines. Countries that once had a strong position in this market may find themselves importing wood pellets or losing market share to nations with more sustainable or abundant forest resources. Thus, from the perspective of the H-O theory, maintaining forest area is crucial for sustaining export performance in forest-based industries [9].

Some variables, however, show adverse effects on the relationship, such as the wood pellet price, inflation, and forest area. A negative effect of price on export performance can be explained using the concept of Price Elasticity of Demand (PED) in international trade. PED measures the responsiveness of the quantity demanded of a good to a change in its price and in the context of export markets, when the demand for a product is price elastic, a rise in export prices leads

to a proportionately larger decline in quantity demanded, resulting in a decrease in total export revenue [47]. In the case of wood pellets, which are considered substitutable commodities in the global market, higher prices can prompt buyers to switch to cheaper suppliers or alternative energy sources. This sensitivity makes export demand highly responsive to price changes.

Therefore, as prices increase, countries may experience reduced competitiveness, especially in price-sensitive markets, leading to a decline in export volumes and market share. Based on an estimation of price elasticity for Malaysia's wood pellet exports, it indicates that Malaysia's wood pellet export demand is highly price-sensitive, with an estimated own-price elasticity of -2.56. This means a 1% increase in Malaysia's export price could reduce export quantity by about 2.56%, confirming that competitive pricing is critical for maintaining market share. In a global market where buyers can easily switch suppliers, Malaysia must prioritize cost efficiency and stable pricing strategies. Additionally, strengthening supply chain reliability and meeting sustainability standards demanded by major importers like Japan and South Korea will help Malaysia secure a stronger position in the growing renewable energy market. These theories and research findings are further supported by the United Nations Conference on Trade and Development, which highlights how price increases can reduce competitiveness and limit market access for exporters [48]. This relationship underlines the importance of maintaining price competitiveness to sustain or enhance export performance in global markets where buyers have multiple sourcing options.

In the case of inflation, it negatively impacts export performance by reducing a country's competitiveness in international markets. When inflation rises, the cost of production increases, leading to higher prices for exported goods and services. This makes exports less attractive to foreign buyers, who may seek cheaper alternatives from other countries [49]. Inflation plays a crucial role in shaping the global trade and market access dynamics, particularly in the wood pellet industry. When inflation rises, production costs, which include raw materials, labor, and transportation, also increase. This leads to higher export prices, making wood pellets less competitive in international markets. Inflation impacts the export performance of wood pellets, particularly by increasing production and transportation costs, making them less competitive in global markets. Rising costs of raw materials, labor, and energy drive up the price of wood pellets, discouraging foreign buyers who may seek cheaper alternatives. Additionally, inflation-related fuel price hikes affect logistics, particularly for exporters relying on truck transportation, further reducing profitability and market access. Studies indicate that transportation costs are a major factor in determining final export prices, with facilities using rail shipping experiencing less impact compared to those relying on trucks [50].

Table 4: *Re-estimation of regression model parameters for wood pellet exports*

Variable	Estimate	Standard Error	P-value
Constant	-182.5000	63.2400	0.03437
Gross Domestic Product	7.0900	1.5770	0.00609
Product Price	0.6160	0.9510	0.54571
Inflation	0.03236	0.1227	0.80259
Forest Area	-0.002344	0.1784	0.99003
Volume of Harvested Roundwood	-9.341e-09	3.186e-08	0.78116

Residual standard error = 0.4976 on 5 degrees of freedom; Multiple R-squared = 0.8683; Adjusted R-squared = 0.7366; F-statistic = 6.594 on 5 and 5 DF; p-value = 0.02949

Re-testing for data normality was shown to have a normal distribution based on the plotting of the remedial Q-Q plot in Figure 4 and the Shapiro-Wilk test statistic (W) of 0.8879, with a p-value of 0.1309 that indicates that the data is normally distributed.

The autocorrelation test using the Durbin-Watson test statistic in Table 5 shows that there is no autocorrelation detected, as the DW statistic is approximately 2 and the p-value > 0.05, thus indicating no significant autocorrelation.

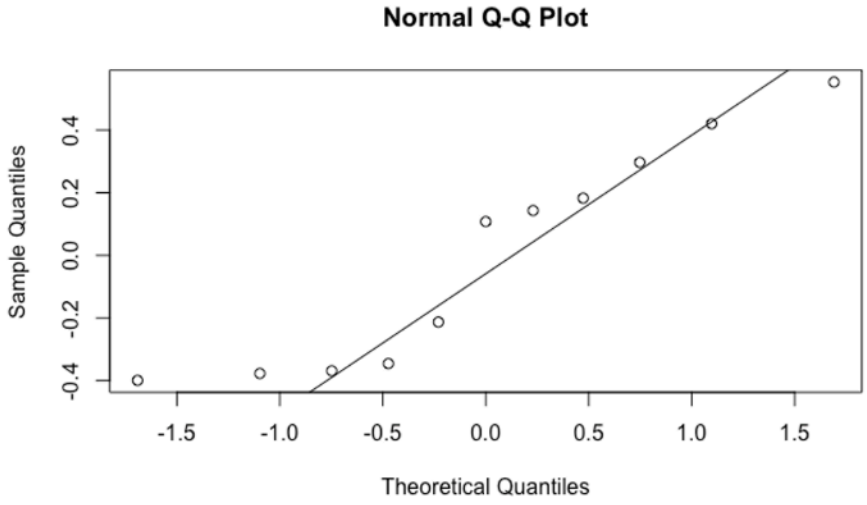

Figure 4: *Remedial QQ plot*

Table 5: *Serial Durbin Watson test for autocorrelation*

Lag	Autocorrelation	D-W Statistic	P-value
1	-0.5101704	2.336067	0.756

VIF was conducted again on the newly estimated model. According to Table 6, the centered VIF values for all variables are less than 10; therefore, this indicates that the assumption of multicollinearity is not violated.

Table 6: *Variance inflation factors analysis for multicollinearity*

ln_gdp	ln_p	inf	area	vol
1.834039	1.301529	1.212587	2.641915	2.622300

4.3. Future research directions

The future development of Malaysia's wood-pellet industry must transcend mere technical optimization to embrace environmental integrity, social equity, and governance innovation. To this end, a multi-dimensional research agenda is required.

Sustainable feedstock management and resource governance is a critical starting point. Research should develop comprehensive biomass-flow mapping and landscape-scale modelling to assess the ecological carrying capacity of biomass sourcing areas. Integrating community-based biomass governance models can ensure that rural and indigenous stakeholders share in both decision-making and benefits. Salleh et al. (2020) demonstrate that Malaysia's bioenergy strategies must incorporate inclusive frameworks to achieve sustainability [68]. Furthermore, expanding carbon accounting and life-cycle transparency is vital. Robust Life Cycle Assessments should incorporate upstream harvesting, processing emissions, transportation to export markets, and indirect land use change. It is crucial, as the global wood energy markets may experience considerable uncertainty when carbon-credit calculations are based on incomplete supply chain information [69].

An equally important action plan is the justice and equity dimensions of a just transition. A just transition is an approach that ensures social equity and economic fairness during the shift from

carbon-intensive systems to more sustainable low-carbon economies. This includes labor rights, equitable value distribution, inclusive procedural frameworks, and recognition of indigenous land rights [70]. According to Zhao and Lo (2025), just transitions can be conceptualized as assemblages using four theoretical building blocks, which include the multiplicity of relations; spatiotemporal embeddedness and dynamic processuality; desire-driven labor and non-human agency; and emergence and uncertainty. Collectively, these building blocks illustrate the effectiveness of the assemblage approach in explaining how just transition practices emerge, evolve, and dissolve, and how power operates within these processes [71]. In terms of technological innovation and accessibility, research should focus on low-emission drying, pelletization, real-time monitoring, and co-product development, such as biochar [72]. However, ensuring access for small and medium enterprises and rural producers is essential to prevent innovation from deepening inequality.

From a policy and certification standpoint, studies should examine Malaysia's integration into international sustainability frameworks such as the Sustainable Biomass Program (SBP), Programme for the Endorsement of Forest Certification (PEFC), and the Forest Stewardship Council (FSC), and analyze emerging mechanisms such as the EU's Carbon Border Adjustment Mechanism (CBAM). The policy frameworks oriented to inclusive governance are needed to catalyze sustainable bioenergy growth [68]. Finally, domestic market diversification and long-term monitoring should be prioritized. Research into rural bioenergy systems using pellets for cooking, heating, or off-grid power can enhance energy equity. Longitudinal environmental and social data collection is needed to monitor biodiversity, forest health, and community wellbeing in biomass-intensive regions [73].

5. Conclusions

The export trend of wood pellets from Malaysia between 2012 and 2023 reveals a dynamic journey of growth, adaptation, and strategic positioning within the global renewable energy market. Initially, Malaysia's wood pellet industry emerged in response to the increasing global demand for sustainable energy sources, particularly from Europe, where policies aimed at reducing carbon emissions created a substantial market for biomass energy. During the early years, Malaysia's exports were modest as the industry focused on building production capacity, improving technology, and establishing itself within these key markets.

As the industry matured, Malaysia saw a period of rapid expansion from 2016 to 2019. Investments in production technology and capacity allowed the country to significantly increase its export volumes. This growth was further bolstered by a successful entry into East Asian markets, notably South Korea and Japan, where the demand for biomass energy was rising as these nations sought to diversify their energy sources and reduce their reliance on fossil fuels. During this period, Malaysia's adherence to international sustainability standards, such as Forest Stewardship Council (FSC) certification, enhanced its reputation and ensured that its products were competitive in environmentally conscious markets [51].

The stabilization phase, which occurred from 2020 to 2021, marked a period during which the Malaysian wood pellet industry reached a level of maturity. Although the COVID-19 pandemic posed challenges, including supply chain disruptions and fluctuating demand, the industry demonstrated resilience. The essential nature of energy products allowed for a relatively swift recovery, emphasizing the critical role that renewable energy sources, including wood pellets, play in global energy security [40]. However, recent years (2022-2023) have introduced new challenges and opportunities for Malaysia's wood pellet exports. Increased competition from new entrants in the global market, particularly from regions such as North America and Russia, has heightened the competitive landscape. At the same time, growing concerns over deforestation and

the environmental impact of large-scale biomass production have led to stricter regulations in key markets, such as Japan and South Korea. These nations began to reassess their biomass energy policies, with a greater emphasis on sustainability and environmental responsibility. Malaysian exporters, already committed to sustainability, needed to further adapt to these evolving regulatory frameworks to maintain their market positions [52]. Moreover, technological advancements in production processes and the focus on producing higher-grade pellets continued to play a crucial role in maintaining Malaysia's competitiveness. The global geopolitical context, including energy security concerns, also influenced market dynamics, providing new opportunities for Malaysian exporters as countries sought to diversify their energy sources away from fossil fuels.

In terms of determinants, factors such as GDP, product price, inflation, the volume of harvested roundwood, and forest area have had significant impacts on Malaysia's wood pellet export trends. Economic growth, as reflected in GDP, has driven both production capacity and demand in export markets. Product pricing, influenced by global market conditions and production costs, has also played a critical role in determining export volumes and competitiveness. Inflation, while a challenge, has been managed within the broader economic context, allowing the industry to maintain its growth trajectory. The sustainable management of forest resources, including the volume of harvested roundwood and the maintenance of forest area, has been crucial in ensuring a steady supply of raw materials, thereby supporting the industry's long-term sustainability.

All in all, Malaysia's wood pellet export industry has navigated various phases of growth, stabilization, and adaptation, demonstrating resilience in the face of global challenges. While the industry has successfully capitalized on its natural resources and market opportunities, it now faces the dual challenges of increased competition and the need for enhanced sustainability practices. Moving forward, Malaysia's ability to innovate, adhere to rigorous environmental standards, and adapt to shifting global market dynamics will be key to sustaining and potentially expanding its role in the global wood pellet market. As the world continues to transition towards renewable energy, Malaysia is well-positioned to contribute significantly to this shift, provided it continues to evolve with the demands of an increasingly sustainability-conscious global market.

Future studies could include additional variables to capture broader influences on Malaysia's wood pellet exports. In particular, a renewable energy policy dummy could represent major policy shifts, such as the implementation of the National Biomass Action Plan, which may significantly affect production and export capacity. Similarly, a COVID-19 dummy for 2019–2021 would account for disruptions in global supply chains and demand during the pandemic. Measures of trade openness or tariff indices could reflect the impact of trade liberalization or restrictions on export competitiveness. If data are available, renewable energy investments or subsidies should be included to capture the role of financial incentives in boosting industry growth.

Beyond these, variables related to the policy and regulatory environment can help explain structural changes in the sector. Incorporating geopolitical and environmental risks, such as regional trade tensions or climate-related disruptions, provides insights into external shocks affecting exports. Finally, indicators of market diversification and demand shifts, such as changes in major importers' preferences or renewable energy targets, would allow researchers to assess how evolving global energy trends influence Malaysia's export performance. These additions would create a more comprehensive model that reflects both economic and non-economic determinants of trade. In essence, Malaysia's wood pellet industry must evolve beyond technical optimization toward a holistic, justice-oriented bioresource model. Integrating sustainability science with equity-based governance can position Malaysia as a regional leader in a fair and sustainable bioenergy transition.

Declaration of interest: The authors declare no conflicts of interest.

References

[1] Proskurina S, Junginger M, Heinimö J, Tekinel B, Vakkilainen E. Global biomass trade for energy—Part 2: Production and trade streams of wood pellets, liquid biofuels, charcoal, industrial roundwood and emerging energy biomass. *Biofuels, Bioproducts and Biorefining* 2018;13(2):371-387.

[2] Goh CS, Junginger M, Cocchi M, Marchal D, Thrän D, Hennig C, Heinimö J, Nikolaisen L, Schouwenberg P, Bradley D, Hess R, Jacobson JJ, Ovard L, Deutmeyer M. Wood pellet market and trade: a global perspective. *Biofuels, Bioproducts and Biorefining* 2013:7(1):24-42.

[3] Jesuet MSG, Samdin Z, Saadun N. Wood-based solid biofuel in Malaysia: Export status and policy review. *Journal of Asian Energy Studies* 2024:8:131-146.

[4] Koh MP, Hoi WK. Sustainable biomass production for energy in Malaysia. *Biomass and Bioenergy* 2003:25(5):517-529.

[5] Klibi W, Trepte K, Rice JB. Make smarter investments in resilient supply chains. MIT Sloan Management Review 2024. Available at: https://sloanreview.mit.edu/article/make-smarter-investments-in-resilient-supply-chains/.

[6] Food and Agriculture Organization of the United Nations. FAOSTAT: Forestry production and trade. FAO 2024. Available at: https://www.fao.org/faostat/en/#data/FO

[7] Herold DM, Marzantowicz Ł. Supply chain responses to global disruptions and its ripple effects: An institutional complexity perspective. *Operations Management Research* 2023:16:2213-2224.

[8] Forest Trends. Vietnam's production and export of wood pellets: Status and some concerns. 2023. Available at: https://www.forest-trends.org/publications/vietnams-production-and-export-of-wood-pellets-status-and-some-concerns/

[9] Lundmark R. European trade in forest products and fuels. Journal of Forest Economics 2010;16(3):235–251. https://doi.org/10.1016/j.jfe.2009.11.007

[10] Krugman P, Obstfeld M, Melitz M. International Economics: Theory and Policy. 12th ed. Pearson; 2022.

[11] Barney JB, Ketchen DJ. Resource-based theory and the value creation framework. *Journal of Management* 2020:46(5):972-980.

[12] Hein E. The macroeconomics of demand-led growth: A Keynesian perspective. *Review of Keynesian Economics* 2023:11(2):145-170.

[13] Jahan A, Al-Harbi T. Global trade dynamics: The effects of tariffs and trade agreements on international business. *International Journal of Economics, Commerce, and Management* 2023:1(2):32-35.

[14] Barney JB, Ketchen DJ. Resource-Based theory and the value creation framework. *Journal of Management* 2020:46(5):972-980.

[15] Bulut E, Yaşar ZR. Determinants of export performance in emerging market economies: New evidence from a panel quantile regression model. *İstanbul İktisat Dergisi - Istanbul Journal of Economics* 2023:73(1):453-472.

[16] Sumiyati EE. Factors affecting manufacturing exports. *Journal of Economics, Business, and Accountancy Ventura* 2020:23(2):254-266.

[17] Nair PSV. Exploring export-led growth in India: A multivariate regression analysis. *IOSR Journal of Economics and Finance* 2024:15:9-12.

[18] Leamer EE. The Heckscher-Ohlin model in theory and practice. *Princeton Studies in International Finance* 1995:77.

[19] Clifton DS Jr, Marxsen WB. An empirical investigation of the Heckscher-Ohlin theorem. *The Canadian Journal of Economics / Revue canadienne d'Economique* 1984:17(1):32-38.

[20] Calzada Olvera B, Spinola D. Determinants of export diversification in resource-dependent economies: The role of product relatedness and macroeconomic conditions. *Structural Change and Economic Dynamics* 2025:74:578-590.
[21] Altıner A, Toktaş Y, Bozkurt E. Determinants of export product diversification: Evidence from developing countries. *The Journal of Social Sciences Research* 2024:19(2):185-195.
[22] Llop M. Quantifying the employment impacts of gross exports: A global accounting perspective. *Journal of Economic Structures* 2022:11:25.
[23] United Nations. UN Comtrade Database. 2025. Available at: https://comtrade.un.org/
[24] Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database. 2025. Available at: https://www.fao.org/faostat/en/
[25] World Bank. World Development Indicators (WDI) Database. 2025. Available at: https://databank.worldbank.org/source/world-development-indicators
[26] Costinot A, Werning I. How tariffs affect trade deficits. NBER Working Paper Series 2024;33709. Available at: http://www.nber.org/papers/w33709
[27] Forestry Department of Peninsular Malaysia. Forestry Statistics. 2025. Available at: https://www.forestry.gov.my/en/2016-06-07-02-53-46/2016-06-07-03-12-29
[28] Sabah Forestry Department. Annual Report. 2025. Available at: https://forest.sabah.gov.my/annual-report/
[29] Forest Department Sarawak. Annual Report. 2025. Available at: https://forestry.sarawak.gov.my/web/subpage/download_list/1113
[30] Wooldridge JM. Introductory econometrics. Cengage Learning, 2019.
[31] Ghauri SP, Qadir H, Ahmed RR, Streimikiene D, Streimikis J. The exports performance of Pakistan: Evidence from the ARDL cointegration analysis. *Romanian Journal of Economic Forecasting* 2022:25(4):150-168.
[32] Greene WH. Econometric analysis. Pearson, 2020.
[33] Mignon V. Principles of econometrics: Theory and applications. Springer, 2024.
[34] Youssef AM. Detecting of multicollinearity, autocorrelation and heteroscedasticity in regression analysis. *Advances* 2022:3(3):140-152.
[35] Asteriou D. Applied econometrics. Bloomsbury Publishing, 2021.
[36] European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). Official Journal of the European Union 2018;L 328:82–209. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001
[37] Ministry of Plantation Industries and Commodities. National Biofuel Policy. Government of Malaysia, 2006.
[38] Agensi Inovasi Malaysia. National Biomass Strategy 2020. Ministry of Energy, 2011. Available at: https://www.energy.gov.my/biomass2020
[39] Malaysian Green Technology and Climate Change Corporation (MGTC). Green Technology Financing Scheme (GTFS) 3.0 Guidelines. Ministry of Natural Resources, Environment and Climate Change, 2021. Available at: https://www.mygtfs.my
[40] Ashraf BN, Goodell JW. COVID-19 social distancing measures and economic growth: Distinguishing short- and long-term effects. *Finance Research Letters* 2022:46:102315.
[41] Liao P, Li F, Li B, Zhang X. COVID-19, social distancing, and economic growth. *Applied Economics* 2021:53(5):577-581.
[42] Lo K. COVID-19 and sustainable energy development: Agendas for future research. *Journal of Asian Energy Studies* 2020:4(1):20-25.
[43] Lukiewska K. Impact of labor productivity on the export performance of the food industry in EU Member States. *European Research Studies Journal* 2022:25(3):74-83.

[44] Rashid M, Azman-Saini WNW. Exchange rate volatility and export performance: Case of Malaysia. *International Journal of Economics* 2024:9(2):1-12.
[45] Subramaniam Y, Masron TA. The impact of economic globalization on biofuel in developing countries. *Energy Economics* 2021:96:105127.
[46] Heckscher EF, Ohlin B. Heckscher-Ohlin trade theory. Edited by Flam H, Flanders MJ. MIT Press, 1991.
[47] Mankiw NG. Principles of economics. 9th ed. Cengage Learning, 2020.
[48] United Nations Conference on Trade and Development. Determinants of export performance. UNCTAD, 2005. Available at: https://unctad.org/system/files/official-document/ditctab20051ch2_en.pdf
[49] Horry A. Global trade dynamics: Understanding macroeconomic effects of trade policies. Sejong University, 2018. Available at: https://www.abacademies.org/articles/global-trade-dynamics-understanding-macroeconomic-effects-of-trade-policies.pdf
[50] Jacob T, Raphael R, Ajina VS. Impact of exchange rate and inflation on the export performance of the Indian economy: An empirical analysis. BIMTECH Business Perspective 2022. Available at: https://bsp.bimtech.ac.in/doi/pdf/10.1177/bsp.2022.3.1.15.pdf
[51] Forest Stewardship Council. The FSC National Forest Stewardship Standard of Malaysia (FSC-STD-MYS-01.1-2021 EN). Forest Stewardship Council, 2021. Available at: https://my.fsc.org/my-en/resources/fsc-malaysia-document
[52] Malaysian Investment Development Authority (MIDA). Carbon pricing: Path towards carbon neutral growth in Malaysia. Malaysian Investment Development Authority, 2023. Available at: https://www.mida.gov.my/carbon-pricing-path-towards-carbon-neutral-growth-in-malaysia/
[53] Lundbäck M, Häggström C, Nordfjell T. Worldwide trends in methods for harvesting and extracting industrial roundwood. *International Journal of Forest Engineering* 2021:32(3):202-215.
[54] Food and Agriculture Organization of the United Nations (FAO). Global Forest Resources Assessment 2025: Country Reports – Malaysia. FAO, 2025. Available at: https://fra-data.fao.org
[55] Singh S, Ali J, Arora R. Linkage between forest cover and trade in forest products: an empirical evidence from BRICS and EU nations. *European Journal of Forest Research* 2024:143(1):19-31.
[56] Lamers P, Junginger M, Hamelinck C, Faaij A. Developments in international solid biofuel trade—An analysis of volumes, policies, and market factors. *Renewable and Sustainable Energy Review* 2012:16(5):3176-3199.
[57] Food and Agriculture Organization of the United Nations (FAO). National forest products statistics, Malaysia. In: An overview of forest products statistics in South and Southeast Asia. FAO, 2002. Available at: https://www.fao.org/4/AC778E/AC778E13.htm
[58] Luong KA, Duong M. Vietnam export wood pellet and woodchip in the first half of 2024. Forest Trends; August 2024. Available from: https://www.forest-trends.org/wp-content/uploads/2025/03/146_Vietnam-exports-wood-pellet-and-woodchip-in-the-first-half-of-2024.pdf [forest-trends.org]
[59] Vietnam Timber and Forest Products Association. Vietnam's wood pellet industry has plenty of room to grow. VnEconomy. March 23, 2025. Available from: https://en.vneconomy.vn/vietnams-wood-pellet-industry-has-plenty-of-room-to-grow.htm
[60] Argus Media. Malaysia's PKS exports fall in 2024, wood pellets rise. March 13, 2025. Available from: https://www.argusmedia.com/en/news-and-insights/latest-market-news/2667206-malaysia-s-pks-exports-fall-in-2024-wood-pellets-rise
[61] Forest Trends. Vietnam's wood pellet export in 6M/2024. March 2025. Available from: https://www.forest-trends.org/wp-content/uploads/2025/03/145_Infographic-wood-pellets-6M_2024.pdf

[62] USDA Foreign Agricultural Service. Japan Biomass Annual 2023. August 10, 2023. Report JA2023-0071. Available at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Japan%20Biomass%20Annual%202023_Tokyo_Japan_JA2023-0071.pdf

[63] For Our Climate. South Korea to reduce government support for biomass energy, sending ripples across Asia. December 17, 2024. Available at: https://forourclimate.org/newsroom/1019

[64] UNECE/FAO. Data Brief 2023: Wood pellets and wood fuel. Geneva: UNECE; 2023. Available at: https://unece.org/sites/default/files/2024-02/2023-data-brief-we-20230205-for%20website.pdf

[65] Brandeis C, Abt KL. Roundwood use by southern wood pellet mills: Findings from timber product output mill surveys. *Journal of Forestry* 2019:117(5):427-434.

[66] Koebel BM, Levet AL, Nguyen-Van P, Purohoo I, Guinard L. Productivity, resource endowment and trade performance of the wood product sector. *Journal of Forest Economics* 2016:22:24-35.

[67] Ibrahim MH, Law SH. Economic growth and macroeconomic factors in Malaysia: A panel data analysis. *Asian Economic Journal* 2014:28(3):289-310.

[68] Salleh SF, Mohd Roslan ME, Abd Rahman A, Shamsuddin AH, Tuan Abdullah TA, Sovacool BK. Transitioning to a sustainable development framework for bioenergy in Malaysia: policy suggestions to catalyse the utilisation of palm oil mill residues. *Energy, Sustainability and Society* 2020:10(1):38.

[69] Johnston CMT, Guo J, Prestemon JP. U.S. and global wood energy outlook under alternative shared socioeconomic pathways. *Forests* 2022:13(5):786

[70] Wang X, Lo K. Just transition: A conceptual review. *Energy Research & Social Science* 2021:82:102291.

[71] Zhao K, Lo K. Assemblage thinking and just transition: Theoretical building blocks of just transition assemblage. *The Extractive Industries and Society* 2025:24:101699.

[72] Li J, Chen Y, Wang C, Chen H, Gao Y, Meng J, Han Z, Van Zwieten L, He Y, Li C, Cornelissen G. Optimizing biochar for carbon sequestration: a synergistic approach using machine learning and natural language processing. *Biochar* 2025:7(1):20.

[73] Ali F, Dawood A, Hussain A, Alnasir MH, Khan MA, Butt TM, Janjua NK, Hamid A. Fueling the future: biomass applications for green and sustainable energy. *Discover Sustainability* 2024:5:156.