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NATURAL RUBBER TRADE AND PRODUCTION TOWARD SUSTAINABLE DEVELOPMENT GOALS: A GLOBAL PANEL REGRESSION ANALYSIS

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Abstract

Natural rubber is one of the most important agricultural commodities used for various purposes around the world. In 2020, the global demand for natural rubber products was approximately 12.5 million tonnes. Over the past decade, the supply of natural rubber increased significantly due to the expansion of plantation areas for natural rubber in Asian countries. Currently, the largest importer of natural rubber is China, accounting for 40% of global consumption and 23.2% of global imports. As global leaders are focusing on achieving the UN's Sustainable Development Goals (SDGs), the debate on sustainable rubber trade and production has escalated. This study investigates the key natural rubber production factors influencing the global natural rubber trade flows. The fixed effects panel regression method was employed to analyze the effects of key factors influencing the import and export of natural rubber. The country-level data were gathered from various international sources such as UN Comtrade, World Bank and FAO. The outcome variables of this study are natural rubber import and export volume, while the explanatory variables include natural rubber harvest area, natural rubber producer price, agricultural support, fertilizer consumption, annual mean temperature and global GDP. The results showed that natural rubber imports and exports are significantly associated with natural rubber harvest area, producer price, agricultural support and annual mean temperature. The findings of this study can be used by policymakers to implement appropriate policies and agricultural supporting schemes to foster sustainable natural rubber trade and production in accordance with the UN's Sustainable Development Goals.

Keywords: Natural rubber, International Trade, Fixed-effects regression, Panel data, Sustainable Development Goals

1. INTRODUCTION

Natural rubber plays a vital role in the global economy, with applications spanning manufacturing, consumer goods, the automobile industry, and medical sectors (Cornish, 2017). Between 2009 and 2013, global rubber demand grew at an average of 5% per year, significantly outpacing the global GDP growth of 1.9% per year during the same period (Khin and Thambiah, 2014; Warren-Thomas et al., 2015; World Bank, 2024). However, the global price

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of natural rubber is highly volatile, with prices ranging from 1,000 USD per ton in 2008 to 6,500 USD per ton in 2011 (Sadali, 2013). This volatility is driven by factors such as the time lag between the planting and yielding of rubber trees, which often leads to oversupply and sharp price declines (Xianhai et al., 2012). For example, after a balanced market between 2004 and 2008, rubber prices dropped by 30% to a five-year low in 2014 due to oversupply (Vongvisouk and Dwyer, 2016). These fluctuations exert considerable pressure on producers and buyers, who must navigate narrow margins and anticipate adverse price movements.

Traditionally, Malaysia, Thailand, and Indonesia, have dominated natural rubber exports (Ali, Akber et al., 2021). However, in recent decades, there has been increased competition from other producers in the Pacific and South Asia. In addition, the interplay between natural and synthetic rubber markets further complicates price dynamics, influenced by the production levels of major rubber-producing countries. Currently, Thailand, Indonesia, Malaysia, and Vietnam, are the world's largest producers and exporters of natural rubber (IRSG, 2022a). These countries benefit from tropical climates conducive to rubber tree cultivation (Hevea brasiliensis), a crop that is labor-intensive and provides livelihoods for millions, especially smallholder farmers (Brahmana et al., 2020). For instance, Thailand alone produces around 4.8 million tons of rubber annually, followed by Indonesia at 3.3 million tons and Vietnam at 1.2 million tons, underscoring the economic importance of the crop for these nations (FAO, 2021a).

The UN's Sustainable Development Goals (SDGs) provide a framework that is particularly relevant for the natural rubber industry, where economic, environmental, and social factors intersect. SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth) are directly relevant, given that many smallholder rubber farmers struggle with low incomes and lack access to secure labor conditions. Furthermore, SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land) emphasize the need for sustainable land management practices and production methods to mitigate deforestation, biodiversity loss, and greenhouse gas emissions commonly associated with rubber plantations. Meanwhile, climate-related goals such as SDG 13 (Climate Action) underline the importance of adopting more sustainable agricultural practices to reduce the carbon footprint of rubber production. By promoting sustainable practices and equitable trade structures, the natural rubber sector can contribute positively to achieving these interconnected goals.

The debate on sustainable natural rubber trade and production has intensified with the global emphasis on achieving the UN's Sustainable Development Goals (SDGs) (Otten, Hein et al., 2020). Natural rubber production directly impacts several SDGs, particularly SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 15 (Life on Land), and SDG 8 (Decent Work and Economic Growth). Environmental concerns include depletion of deep-soil moisture, groundwater, and streamflow, as well as increased evapotranspiration compared to native crops (Kobayashi et al., 2014; Tan et al., 2011). Additionally, the conversion of forests to rubber plantations significantly reduces biodiversity and alters species composition, directly affecting SDG 15 (Warren-Thomas et al., 2015). Socially, large-scale rubber plantations are linked to poor labor conditions and evictions, underscoring challenges related to SDG 8 (Baird, 2010; OHCHR, 2007).

In recent years, efforts to align rubber production with the SDGs have gained momentum, driven by both governmental and non-governmental initiatives (Yunus et al., 2020). These include sustainable certification programs, reforestation and conservation projects, and value chain transparency initiatives that seek to improve environmental stewardship and fair labor practices (Panbamrungkij, 2024). Additionally, innovations in agroforestry, circular economy approaches, and green finance have the potential to transform the industry by reducing its ecological impact and enhancing socioeconomic outcomes for farmers and communities. Despite these advancements, challenges such as market fluctuations, limited farmer education, and a lack of robust policy frameworks hinder the effective implementation of sustainable practices across the global rubber supply chain (Aziz et al., 2019).

1.1. Research Questions and Hypotheses

This study aimed to address the following research questions:

1.1.1. What are the key factors influencing natural rubber trade development?
1.1.2. How does natural rubber price affect natural rubber trade flows?
1.1.3. Which external factors such as temperature and global GDP influence natural rubber trade flows?

To answer these questions, we hypothesize that:

H1: Production related factors such as natural rubber harvest area, agricultural support, and fertilizer consumption rate, significantly impact natural rubber trade flows, contributing to the achievement of the SDGs.

H2: Higher natural rubber producer price is significantly associated with natural rubber trade flows.

H3: External factors such as climate and global GDP play a vital role in natural rubber trade flows.

1.2. Theoretical Framework and Model Predictions

To explore these hypotheses, panel regression models were employed to analyze the relationship between natural rubber production and external factors and natural rubber trade flows. The panel regression models were designed to predict the impact of these factors on natural rubber trade volumes, thereby linking the outcomes to the SDGs. For instance, a positive coefficient for factors related to natural rubber harvest area in the regression model would indicate that factors contribute to SDG 12 by promoting responsible consumption and production.

The models aim to predict the key factors associated with natural rubber trade inflows and outflows, separately.

1.3. Research Objectives

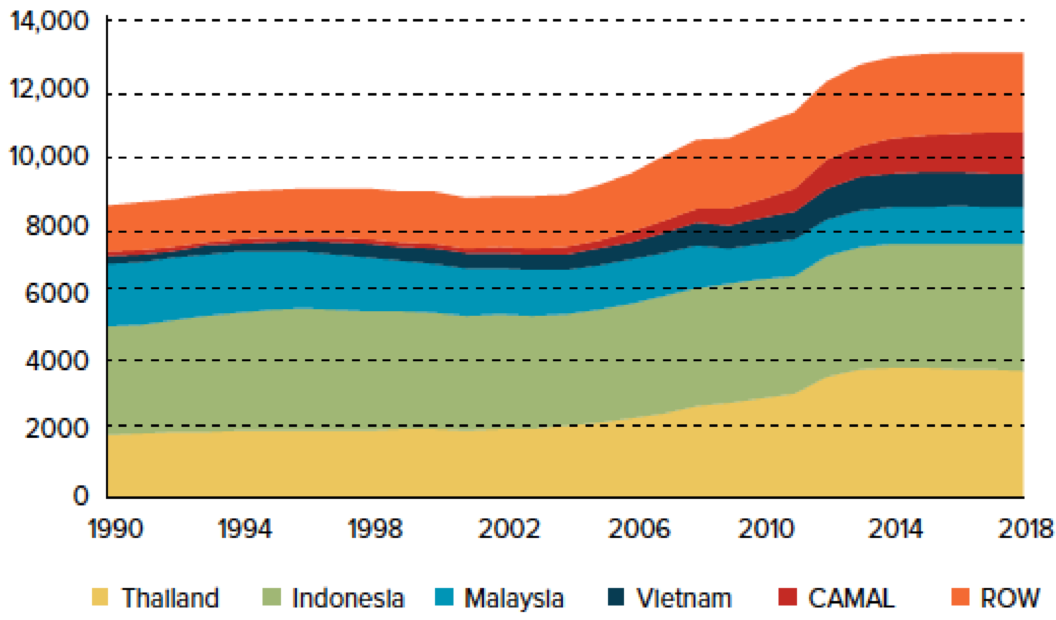
The main objective of this research is to analyze the key production and external factors associated with sustainable natural rubber trade flows using the panel regression analysis method. By highlighting the factors that drive sustainable development in the natural rubber trade sector, this study aims to inform policymakers and stakeholders on natural rubber trade strategies that align with the SDGs, thereby enhancing the sector's contribution to sustainability goals. Understanding these dynamics is crucial for agricultural economies such as Thailand, Malaysia, and Indonesia, where the balance between economic growth and sustainable practices is imperative.

2. LITERATURE REVIEW

Natural rubber is one of the world's primary economic crops. Currently, the biggest importers of natural rubber are China, Europe, India, USA, and Japan (Arunwarakorn, 2017). In China, the demand for natural rubber is driven by industries that rely heavily on using rubber as raw material such as the automobile and tire industries (Pitakpaibulkij et al., 2015). Over the last few years, the global prices of natural rubber have declined due to an oversupply issue (Reportlinker, 2015). The International Rubber Study Group (IRSG) predicted that the natural rubber market will experience an oversupply issue for many years into the future (IRSG, 2016a). Consequently, many rubber producing countries have reduced their production levels in an attempt to reduce the oversupply situation (Verico, 2013).

In 2020, the total amount of rubber plantations worldwide encompassed approximately 14.1 million hectares (IRSG, 2020). It is estimated that the rubber plantation area has almost doubled over the past 3 decades. Figure 1 shows the dynamic changes of global rubber expansion from 1990 to 2018.

Figure 1. Rubber Plantation Area (thousand hectares) from 1990 to 2018

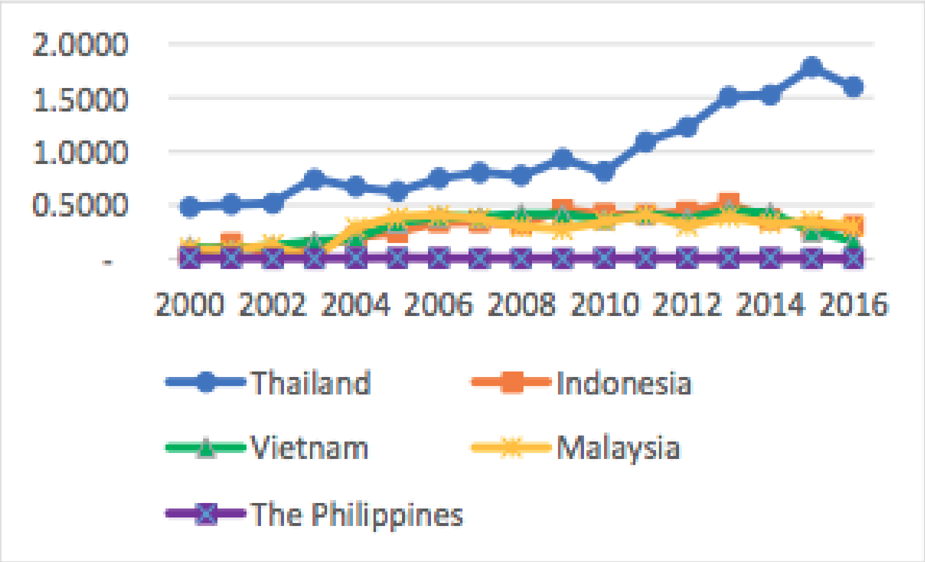


*CAMAL = Cambodia, Myanmar, and Laos. ROW = Rest of the world
Source: IRSG 2020a

As shown in Figure 1, there are several significant changes in the global rubber plantation landscape. First, the global plantation area increased significantly from just over 8 million hectares in 1990 to around 13 million hectares in 2018. Second, Malaysia and Indonesia experienced noticeable stagnation in rubber plantation area, whereas rubber plantation area in Thailand has increased significantly. Third, there has been a sharp increase in rubber plantation area in Cambodia, Myanmar and Laos (CAMAL) compared to the rest of the world (ROW).

It is undeniable that the high growth in global natural rubber demand comes from China (Ali, Akber et al. 2021). China is currently the world's second largest economy and the world's largest importer of natural rubber. It accounts for 40% of global rubber consumption and 23% of global rubber imports (Kennedy et al., 2017). In particular, the rapid growth of the automobile and tire industries in China has driven the demand for natural rubber significantly (Oktora, 2019). Currently, China heavily relies on importing natural rubber from Southeast Asian countries. Many studies have analyzed the impact of China's slowdown on international trade, especially within Asia. Blagrave and Vesperoni (2016) suggested that China's trading partners will face lower demand for exports, with the degree of this effect depending on countries' sectoral linkages with the Chinese economy. Dizioli, Hunt, and Maliszewski (2016) investigated the impact of China's economic slowdown on the economies of countries that it has strong links with, such as the Southeast Asia countries. Figure 2 illustrates the export volume trend of natural rubber among major rubber producing countries in Southeast Asia (Thailand, Indonesia, Malaysia, Vietnam, and Philippines) to China from the year 2000 to 2016.

Figure 2 Export Volume (in million tonnes) of Natural Rubber Between ASEAN Countries and China from 2000 to 2016



Source: FAOSTAT

As shown in Figure 2, natural rubber exports to China are dominated by Thailand. This is followed by Indonesia, Malaysia, Vietnam, and The Philippines, respectively. Exports from Thailand to China grew from 0.48 million tonnes in 2000 to 1.78 million tonnes in 2015. In contrast, the total exports of Indonesia, Malaysia, Vietnam, and The Philippines, gradually declined from 2000 to 2016. It is believed that the impact of China's slowdown in economic growth continues to affect rubber export volume from the Southeast Asian countries to China.

Natural rubber export price is an important factor that affects the amount of natural rubber that can be sold abroad and imported by the destination country (Oktora, 2003). When the natural rubber price of exporting countries is high, the exporting countries will further increase the number of commodities to be sold abroad. Thus, the number of items that can be imported by the destination country will be even greater. Natural rubber price instability, one of which is caused by the economic slowdown in developed and developing countries could affect the economic performance of exporting countries in many ways (Raju, 2016). Global economic growth had provided a boost for growth in the automotive industry which has led to an increase in natural rubber production. However, the recession which occurred in 2008-2012 affected the growth of the automotive sector and resulted in a lack of demand for natural rubber (Raju, 2016).

Natural rubber varies in quality depending on factors such as source of latex, tree age, and processing methods, all of which affect its elasticity, purity, and overall performance. Premium grades, such as Ribbed Smoked Sheets (RSS) 1 and Technically Specified Rubber (TSR) 20, are recognized for their consistent quality, low impurity levels, and enhanced durability, which make them suitable for high-demand applications like tires and medical supplies (Ciesielski, 2020). Given these quality differences, prices often reflect the grade and intended use of the rubber. Higher-quality rubber, which undergoes more rigorous processing to ensure minimal contaminants and stable properties, generally commands a higher price due to increased production costs and specialized applications (Ismail & Abu Bakar, 2021). Therefore, in the natural rubber market, price tends to correlate with quality, reflecting the diverse industrial specifications that different grades of rubber meet (Rimawan et al., 2021).

The natural rubber market is highly volatile, with prices influenced by a combination of supply-side factors, including weather patterns, disease outbreaks, and production costs, and demand-side drivers, such as global economic trends and the automotive industry's performance. This volatility complicates trade dynamics, as fluctuations in prices can significantly affect the import and export strategies of rubber-producing and consuming countries. For instance, when prices drop, producers in major exporting countries like Thailand, Indonesia, and Malaysia, often struggle with reduced income, potentially leading to decreased production capacity in the long term. Conversely, higher prices may encourage importing countries to seek synthetic alternatives, affecting demand for natural rubber. Additionally, currency exchange rates and geopolitical tensions can further exacerbate these complexities, creating uncertainties for stakeholders across the supply chain (FAO, 2021b; IRSG, 2022a).

Furthermore, an increase in the producer price of natural rubber often reflects a shift toward the production of higher-quality rubber, driven by market demand for premium materials. This trend can have a dual impact on trade and domestic consumption. As producers focus on high-quality rubber to capture better market prices, they may allocate fewer resources to producing lower-quality grades. This creates a gap that could stimulate the import of low-quality rubber to meet the needs of industries where premium quality is unnecessary, such as in some types of tire manufacturing or other industrial applications. Simultaneously, higher domestic demand for high-quality rubber—driven by sectors such as automotive, medical, and high-performance industrial goods—further reinforces this price dynamic. This situation illustrates the interconnectedness of global trade and domestic market demands, where pricing signals can alter production strategies and trade flows significantly (FAO, 2021b; IRSG, 2022b).

There are many factors which contribute to the development of sustainable natural rubber trade and production toward achieving the UN's SDGs. Gitz et al. (2020) suggested that the diversity of economic and production models as well as diversity in policies and measures, are important for achievement of sustainable rubber trade and production in accordance to the UN's SDGs. For instance, land use for natural rubber plantations is a central issue for achievement of the SDGs (Gitz et al., 2020). Natural rubber production is largely dominated by smallholders. It is estimated that around 90% of global production of natural rubber comes from smallholdings (IRSG, 2019). Smallholders can be either independent or linked to companies by contract farming. For natural rubber producing countries in Southeast Asia, the production systems can be categorized into three main types: independent smallholder production, estate plantations, and contract farming between companies and farmers (Kenney-Lazar et al., 2018).

Contract farming in natural rubber-producing countries, such as Thailand, Indonesia, and Vietnam, plays a vital role in advancing the United Nations Sustainable Development Goals (SDGs), particularly those related to poverty alleviation (SDG 1), decent work (SDG 8), and responsible production (SDG 12). By providing smallholder farmers with inputs, technical guidance, and price guarantees, contract farming helps stabilize incomes, reduce poverty, and foster inclusive economic growth in rural communities (FAO, 2020). This model also supports gender equality (SDG 5), as women involved in rubber farming benefit from better access to resources and financial security under contract arrangements (Amanor & Pabi, 2021). Furthermore, contract farming promotes responsible production by establishing environmental standards, such as sustainable land management and chemical usage, aligning with SDG 12 (UNCTAD, 2022). Additionally, companies that engage in contract farming often encourage sustainable farming practices to meet global demand for eco-friendly rubber, contributing to climate action (SDG 13) and fostering long-term environmental sustainability (Chen et al., 2021). While contract farming has challenges, including the potential for dependency and unequal power relations, its structured support system helps smallholders align with broader sustainable development objectives.

Natural rubber production supports millions of smallholder farmers in Southeast Asia, contributing directly to SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth) by providing employment and income opportunities in rural areas (Brahmana et al., 2020). Studies have shown that rubber farming can offer a reliable income, but the volatility of rubber prices poses a significant challenge to financial stability for smallholders (Choocharoen et al., 2021). This price instability often leaves farmers vulnerable to poverty, making them reliant on government subsidies or international aid in times of low demand (IRSG, 2022b).

Research has suggested that fair trade practices and value chain improvements could provide more stable incomes for rubber farmers, enabling them to withstand market fluctuations (Aziz et al., 2019). Innovations in market access and digital trading platforms may further empower smallholders by linking them directly to buyers and reducing dependency on intermediaries (Shahbandeh, 2021). However, Brahmana et al. (2020) argue that economic empowerment initiatives must be complemented by educational programs, financial literacy training, and access to financial services to enable farmers to make informed decisions and build resilience against economic shocks.

Moreover, natural rubber production is closely linked to environmental sustainability, as rubber plantations have been associated with deforestation, soil degradation, and loss of biodiversity, particularly in Southeast Asia (WWF, 2021). This challenges the sector’s alignment with SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land), which emphasize sustainable resource management and ecosystem preservation. Researchers have noted that rubber plantations often replace primary forests, contributing to habitat loss for numerous species (Ziegler et al., 2020). Expansion into forests and other natural areas not only threatens biodiversity but also disrupts the hydrological cycle and increases carbon emissions (Yunus et al., 2020).

Climate change also poses both direct and indirect challenges to natural rubber production, with unpredictable weather patterns affecting latex yields and rubber tree health. SDG 13 (Climate Action) emphasizes the need to enhance resilience and adaptive capacity to climate-related hazards, a pressing concern for the natural rubber sector. Research suggests that agroforestry, which integrates rubber trees with other crops or forest species, offers a promising strategy for increasing resilience to climate change, reducing the environmental footprint of rubber production, and improving biodiversity (Ahmad et al., 2021). Agroforestry systems have been shown to enhance soil health, improve water retention, and increase carbon sequestration compared to traditional monoculture rubber plantations (Yunus et al., 2020).

This research attempts to analyze the key factors associated with the development of sustainable natural rubber trade and production by using country-level panel data gathered from various international reputable sources observed over multiple years by using a panel data regression method. The panel data regression model has been used by several researchers to analyze panel data. Zheng, Shao, and Wang (2017) employed the panel regression model to analyze the import and export of Chinese non-ferrous metals. The study used data from several countries as cross-section units and several periods as time series units. Eberhardt and Teal (2010) used the Augmented Mean Group (AMG) model to study productivity in global manufacturing production. Atasoy (2017) also employed the same model to test the Kuznets curve hypothesis.

3. METHODS AND MATERIALS

3.1 Data Collection

This study gathers country-level annual data from 190 countries distributed around the world. The data were collected annually for 20 years from the year 2001 to 2020. The country-level data used in this study comes from various reliable sources. The collected data can be classified into three categories; trade, production and external factors. The natural rubber import and export volumes (in tons), which represent trade flows were gathered from UN Comtrade. The production variables, including natural rubber harvest area (hectares), producer price (USD per ton), agricultural support, and fertilizer consumption rate, were gathered from FAOSTAT. For the external factors, the country level annual mean temperature and global GDP were collected from the World Bank.

The key variables in this study included natural rubber import and export volume, natural rubber harvest area, natural rubber producer price, agricultural support, fertilizer consumption, annual mean temperature, and global GDP. Furthermore, this research aims to analyze the key determinants of global natural rubber trade flows by using the fixed effects panel regression method. The dependent variables in this study are the import and export volume of natural rubber. The explanatory variables in this study include natural rubber harvest area (hectares), agricultural support, fertilizer consumption, annual mean temperature, and global GDP.

Table 1 Variables Used for the Analysis of Sustainable Natural Rubber Production and Trade Flows

Variable	Definition	Relevant SDGs	Unit of measurement	Source
Dependent variables				
Natural rubber import	Total import volume of natural rubber per country in metric tons.	SGD 8 (Decent Work and Economic Growth) - Encourages trade as a means of boosting economic growth.	Metric tons	UN Comtrade
Natural rubber export	Total export volume of natural rubber per country in tons.	SDG 17 (Partnerships for the Goals) - Promotes global trade partnerships.	Metric tons	UN Comtrade
Independent variables				
Natural rubber harvest area	Total area harvested for natural rubber in hectares per country.	SDG 15 (Life on Land) - Promotes sustainable land use and management. SDG 12 (Responsible Consumption and Production) - Encourages efficient use of land resources and sustainable agriculture.	Hectares	FAOSTAT
Natural rubber producer price	Natural rubber producer price in USD per ton.	SDG 8 (Decent Work and Economic Growth) - Affects economic viability and fair pricing for producers. SDG 10 (Reduced Inequalities) - Promotes fair	USD per ton	FAOSTAT

Table (Continued)

Variable	Definition	Relevant SDGs	Unit of measurement	Source
		income distribution for farmers and producers.		
Agricultural Support	Total percentage of agricultural support relative to the country's GDP.	SDG 2 (Zero Hunger) - Enhances food security through support for agriculture. SDG 8 (Decent Work and Economic Growth) - Supports economic resilience in the agricultural sector.	Percent	FAOSTAT
Fertilizer Consumption	Total consumption of fertilizer in kilograms per hectare by country.	SDG 2 (Zero Hunger) - Increases agricultural productivity through effective fertilizer use. SDG 12 (Responsible Consumption and Production) - Promotes responsible use of agricultural inputs.	Kilograms per hectare	FAOSTAT
Temperature	Country's annual mean temperature in degrees Celsius.	SDG 2 (Zero Hunger) - Ensures sustainable agricultural practices under changing climatic conditions. SDG 13 (Climate Action) - Highlights the impact of climate on agriculture and trade.	Celcius	World Bank
Global GDP	The monetary value of all finished goods and services made during a specific period for the whole world.	SDG 8 (Decent Work and Economic Growth) - GDP growth reflects overall economic productivity and contributes to sustainable economic growth. SDG 9 (Industry, Innovation, and Infrastructure) - Economic growth can be driven by innovation and infrastructure development.	US Dollar	World Bank

Table 1 summarizes the details and definitions of the variables included in this study. As detailed in Table 1, the dependent variables, natural rubber imports and exports are defined as the total import and export volume of natural rubber per country measured in metric tons. The relevant SDGs include SDG 8 and SDG 17. Natural rubber harvest area refers to the total harvested area of natural rubber per country measured in hectares (SDG 12 & SDG 15). Natural rubber producer price is defined as the producer price in a given year in USD per metric ton (SDG 8 & SDG 10). Temperature refers to the annual mean temperature of each country measured in degrees Celcius (SDG 2 & SDG 13). Agricultural support refers to the total agricultural support in terms of percentage relative to a country's GDP (SDG 2 & SDG 8). Fertilizer consumption refers to total usage of fertilizer measured in kilograms per hectare in the given country. Finally, global GDP refers to the total monetary value of all finished goods and services made during a specific period across the world (SDG 8 & SDG 9).

3.2 Data Modelling

This research gathers annual country-level panel data from 190 countries from the year 2001 to 2020. Data were collected from various international sources such as the World Bank, FAOSTAT, and UN Comtrade. The main objective of this study was to analyze the key production and external factors that are significantly associated with natural rubber trade flows. In this study, the assigned dependent variables, which represent the trade flows of natural rubber are the import and export volume of natural rubber. The assigned independent variables include natural rubber harvest area, producer price, annual mean temperature, agricultural support, fertilizer consumption, and global gross domestic product (GDP).

It is essential to clarify that this study does not attempt to derive or estimate a demand nor supply curve. Rather, the objective is to investigate the empirical relationships between natural rubber trade flows and key independent variables, without implying a demand or supply framework. In other words, this study aims to provide an analysis of how domestic and externatal factors influence international rubber trade flows, without implying estimated demand or supply curves. This distinction will be further elucidated in the interpretation of results.

This study ultilizes both exports and imports as key dependent variables. Using both exports and imports as separate dependent variables in a regression model can provide richer insights compared to a model with only net exports (exports minus imports) as the dependent variable. By modeling exports and imports independently, one can better understand the distinct factors driving each. For example, export levels may respond to factors such as foreign demand, domestic production capacity, or exchange rates, while imports might be influenced by domestic consumption, availability of substitutes, and trade policies. Combining these distinct perspectives within one model can reveal how different economic forces impact each side of the trade flows, which is masked when using net exports alone. Furthermore, analyzing exports and imports separately avoids the risk of offsetting effects that could occur in net export analysis. Therefore, treating exports and imports separately enhances the model's accuracy and interpretability, providing a clearer picture of trade dynamics and allowing for more tailored policy insights.

For the empirical analysis, the fixed effects regression method is used to analyze the key factors associated with natural rubber trade flows (Srisawasdi et al., 2023). The equations for the panel fixed effects regression models can be expressed as follows;

$$\mathrm{IMP}_{it} = \mathrm{c} + \alpha_1\mathrm{ARE}_{it} + \alpha_2\mathrm{PRI}_{it} + \alpha_3\mathrm{TEM}_{it} + \alpha_4\mathrm{AGT}_{it} + \alpha_5\mathrm{FER}_{it} + \alpha_6\mathrm{GDP}_{it} + \epsilon_{it} \quad (1)$$

$$\mathrm{EXP}_{it} = \mathrm{c} + \beta_1\mathrm{ARE}_{it} + \beta_2\mathrm{PRI}_{it} + \beta_3\mathrm{TEM}_{it} + \beta_4\mathrm{AGT}_{it} + \beta_5\mathrm{FER}_{it} + \beta_6\mathrm{GDP}_{it} + \epsilon_{it} \quad (2)$$

Where the entities (countries) i are observed across time t, IMP_{it} and EXP_{it} represent the import and export quantity of natural rubber (in metric tons), ARE_{it} is the area of natural rubber harvested, PRI_{it} is the natural rubber producer price, TEM_{it} is the annual mean temperature, AGT_{it} is agricultural support, FER_{it} is the fertilizer consumption rate (kg/ha), GDP_{it} is the global gross domestic product, α is a coefficient for equation (1), β is a coefficient for equation (2), c is a constant and ε_{it} is the error term.

4. RESULTS

Table 2 provides a summary of the descriptive statistics of key variables in the analysis of this study. The sample size for this study is 3,800. In terms of the arithmetic mean, the average values for natural rubber imports and exports are 12,179 and 11,653, respectively. The arithmetic mean for natural rubber harvest area, producer price, annual mean temperature, agricultural support, fertilizer consumption, and global GDP, are 32,695, 55.7, 20.09, 0.09, 148.03, and 64,902.04, respectively. The standard deviation for natural rubber imports, exports, production, producer price, annual mean temperature, agricultural support, fertilizer consumption, and global GDP are 84,343, 93,584, 259,614, 319.54, 7.88, 0.39, 722.11 and 17,147.84, respectively. The minimum values for natural rubber imports, exports, production, area harvested, producer price, temperature, agricultural support, fertilizer consumption, and global GDP are 0, 0, 1,000 , 5, 5, 0, 0 and 33,852.56, respectively. The maximum values for natural rubber imports, exports, production, producer price, annual mean temperature, agricultural support, fertilizer consumption, and global GDP are 1,000,000, 1,000,000, 3,500,000 , 3,000, 35, 1, 19,171.85, and 87,494.08, respectively.

Table 2 Descriptive Statistics Summary for Key Variables (sample size n = 3,800)

Variable	Mean	Std. Dev.	Min	Max
Natural rubber imports	12,179	84,343	0	1,000,000
Natural rubber exports	11,653	93,584	0	1,000,000
Natural rubber harvest area	32,695	259,614	1,000	3,500,000
Natural rubber producer price	55.70	319.54	5	3,000
Annual mean temperature	20.09	7.88	5	35
Agricultural support	0.09	0.39	0	1
Fertilizer consumption	148.03	722.11	0	19,171.85
Global GDP (in billion USD)	64,902.04	17,147.84	33,852.56	87,494.08

The empirical analysis examines the factors that influence the flow of natural rubber imports and exports using a fixed effects regression model with country-level panel data. Table 3 reveals the fixed effects regression results for the imports and exports regression models. The findings of the analysis demonstrate that natural rubber harvest area has a highly significant positive relationship with both imports and exports. Specifically, an increase of one hectare in area harvested leads to an increase of 0.061 tons in imports and 0.055 tons in exports. This suggests that larger natural rubber harvest area can stimulate both the import and export sectors. The similarity of the coefficients suggests a more complex dynamic, possibly influenced by global supply chain networks or the dual role of countries as both importers and exporters of natural rubber.

The analysis also examines the impact of natural rubber producer price, revealing contrasting effects on natural rubber imports and exports. A one USD per ton increase in price leads to a 4.249 ton increase in imports. On the contrary, a one USD per ton increase in price results in a 4.028 ton decrease in exports. One possible interpretation is that higher prices may reduce export competitiveness in the global market, but boosts demand for importation of natural rubber. Furthermore, the impact of agricultural support on both imports and exports is highly significant. A one percent increase in agricultural support results in a considerable decrease of 24,758.64 tons in imports and 32,751.91 ton decrease in exports. These findings suggest that higher levels of domestic agricultural support may help to stabilize domestic markets for natural rubber, thus reducing the need for both importing and exporting. There is no significant relationship between fertilizer consumption and trade flows. This indicates that variations in fertilizer usage per hectare do not significantly affect natural rubber imports or exports.

In terms of external factors, temperature shows a significant negative relationship with natural rubber imports and exports. A one-degree Celsius increase in annual mean temperature is associated with a reduction of 680.509 tons of natural rubber imports, and 442.329 tons in exports. This implies that higher temperatures may have a negative impact on natural rubber production and, subsequently, trade volumes. However, global GDP does not show significant relationships with natural rubber imports and exports.

Table 3 Fixed Effects Regression Results

Variable	Model 1. Natural Rubber Import		Model 2. Natural Rubber Export	
	Coefficient	Standard Error (SE)	Coefficient	Standard Error (SE)
Natural Rubber Harvest Area (hectares)	0.061***	0.002	0.055***	0.002
Natural Rubber Producer Price (USD per ton)	4.249**	1.892	-4.028**	1.999
Agricultural Support (% of GDP)	-24,758.64***	2,864.326	-32,751.91***	3,641.4
Fertilizer Consumption (kilograms per hectare)	-0.155	0.737	-0.119	0.763
Annual Mean Temperature (Celsius)	-680.509***	182.674	-442.329*	237.031
dGlobal GDP (in billion USD)	-0.019	0.028	-0.031	0.035
Constant	27,762.56***	4,098.2	25,296.8***	5,281.983
R-squared	0.2734		0.2108	

Note. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

The constant values in both models are highly significant, indicating significant baseline levels of imports and exports when all other variables are held constant. These large constant values reflect significant levels of trade in natural rubber. The r-squared values for the models are 0.2734 for imports and 0.2108 for exports, indicating that the models explain 27.34% and 21.08% of the variability in natural rubber imports and exports, respectively. This indicates a good fit of the models to the data, capturing the variability in trade flows.

5. DISCUSSION

Hypothesis 1 asserts that production related factors such as natural rubber harvest area, domestic agricultural support, and fertilizer consumption rate, significantly impact natural rubber trade flows. The study confirms significant associations between increased natural rubber harvest area and higher trade volumes for natural rubber. Furthermore, agricultural support is found to have statistically significant negative effects on both imports and exports. These findings emphasize the significance of natural rubber harvest area and domestic agricultural support, especially in countries such as India, where increased production area and agricultural support can stabilize the market but may restrict trade intensity.

Another possible explanation for the negative effects of domestic agricultural support on natural rubber trade flows is that bigger countries that spend more on agricultural support such as China and India do not play a significant role in the global natural rubber trade and production. Therefore, the effects of agricultural support may increase trade volumes of other cash crops prioritized by big countries such as China and India, instead of natural rubber, which is mainly produced and exported by smaller countries such as Thailand, Malaysia and Indonesia.

Furthermore, the analysis revealed no significant effect between fertilizer consumption rate and natural rubber trade flows. This suggests that, while factors such as area harvested and producer price are vital in determining trade dynamics, other agricultural inputs such as fertilizer may not directly impact natural rubber imports and exports. This complexity in material and energy flows within the natural rubber trade is noted by Nakajima et al. (2018), who emphasized the importance of reducing resource consumption for sustainable development.

Technological advancements have significantly transformed agricultural productivity over the past century (Ngatindriatun and Adzim, 2022). Breeding programs, improved agronomic practices, and efficient exploitation systems have resulted in considerable yield increases for natural rubber (Kadir, 1994). However, smallholders encounter challenges in adopting these new, socially beneficial technologies due to constraints related to credit and information (Barlow & Jayasuriya, 1984). Recent research has expanded our understanding of natural rubber biosynthesis, with omics technologies providing new insights into rubber production and the development of alternative rubber-producing plants (Men et al., 2018). Nonetheless, the expansion of rubber plantations into non-traditional areas, aided by new hybrid varieties, raises concerns about environmental and social impacts, including biodiversity loss, increased chemical usage, and potential land loss for smallholders (Fox, 2014). These developments highlight the complex interplay between technological progress and sustainable natural rubber production.

Hypothesis 2 stated that natural rubber price is negatively associated with natural rubber trade flows. Natural rubber price is a critical issue in natural rubber trade, closely tied to global economic conditions. The study reveals that rising natural rubber price leads to decreased exports, illustrating the complex relationship between demand and supply. This finding supports Hypothesis 2, which posits that natural rubber price significantly impacts trade flows by influencing natural rubber demand and supply. As natural rubber prices rise, importing countries such as China may boost demand to stabilize supply chains (Li, 2013), while exporting nations face reduced competitiveness due to higher costs.

Sitepu et al. (2016) highlight that price volatility results in significant trade-offs among economic, environmental, and social sustainability. During periods of market unpredictability, producers are less likely to invest in sustainable technologies or long-term practices, aligning with the observation that volatility discourages sustainable practices. To mitigate this volatility and promote sustainable production, policy interventions are essential, particularly in line with SDG 12 (Responsible Consumption and Production). Addressing these issues is crucial, given the broader macroeconomic risks impacting global trade flows, as discussed by Yatsenko et al. (2018), who emphasize the intersection of global risks with trade and economic policies.

The International Natural Rubber Agreement (INRA) played a significant role in regulating the global natural rubber trade from 1979 until its collapse in 1999 (Verico, 2013). This agreement influenced both global supply and Indonesia's economy, as analyzed using the Cournot-Nash Equilibrium and Input-Output Table Simulation approaches (Verico, 2013). The INRA introduced joint responsibility for financing international stocks, though it reduced the regulatory scope (Khan, 1980). In recent developments, the ASEAN-India Free Trade Agreement (AIFTA) has become prominent in the rubber sector. India, a major producer, consumer, and trader of natural rubber and rubber products, has been involved in this agreement (Joseph & Hari, 2019). However, trade indicators such as revealed comparative advantage and intra-industry trade suggest that AIFTA has not significantly altered India's export patterns or the specialization in rubber and rubber products within the ASEAN countries (Joseph & Hari, 2019).

Hypothesis 3 is supported by evidence indicating that external factors, such as climate change, significantly impact natural rubber trade. Higher temperatures negatively affect both natural rubber imports and exports, showing that climate variability—an important external factor—directly influences rubber production and trade flows. This underscores the necessity for robust climate action strategies within the natural rubber industry, in line with SDG 13 (Climate Action). The decline in trade volumes due to climate-induced factors highlights the importance of adaptive strategies to mitigate the adverse effects of rising temperatures on crop yields.

In Nigeria and the Philippines, rubber farmers are employing various strategies to adapt to climate change. Common measures include intercropping, adjusting planting dates, and utilizing indigenous techniques such as applying firewood ash to control root rot (Otene et al., 2017). Agroforestry and diversified farming systems have proven effective adaptation strategies in both countries (Furoc-Paelmo et al., 2019; Furoc-Paelmo et al., 2018). Additional strategies include fire tracing, mulching, and engaging in off-farm activities (Ik & Tu, 2015). Farmers in the Philippines are also reducing their use of inorganic fertilizers and pesticides, opting for organic farming practices instead (Furoc-Paelmo et al., 2019). Despite these efforts, farmers face challenges such as low capital, inadequate infrastructure, high input costs, and limited information on climate change (Otene et al., 2017). To overcome these obstacles, researchers recommend strengthening extension services, increasing awareness about climate change, and improving access to financial resources and weather information (Ik & Tu, 2015).

Other various factors influence the global trade of natural rubber, including economic conditions, policies, and market dynamics. For instance, China's natural rubber imports are significantly affected by the state of the global economy, product composition, and macroeconomic policies (Li, 2013). In India, the availability of local production and the pricing of natural rubber play crucial roles in shaping both production and export levels (Kannan, 2013). Global economic crises also impact natural rubber prices, which are driven by overarching macroeconomic conditions and governmental policies from countries such as China (Xin, 2009). In Indonesia, key determinants of natural rubber exports include distance, exchange rates, population, and GDP (Purmiyati, 2020).

The natural rubber trade and production sector has significant potential to advance the UN's SDGs, especially those focusing on economic growth (SDG 8), sustainable industry (SDG 9), and climate action (SDG 13). The production area for natural rubber is concentrated in countries such as Thailand, Indonesia, and Malaysia, where it serves as a key income source for millions of smallholders, supporting poverty reduction (SDG 1) and economic growth in rural communities (FAO, 2020). To align with responsible consumption and production (SDG 12), there is an increasing focus on sustainable practices in rubber cultivation, including reduced pesticide use, agroforestry integration, and improved land management to prevent deforestation (UNCTAD, 2022). Additionally, the global shift toward sustainable sourcing, driven by multinational companies and international standards, is encouraging rubber producers to adopt eco-friendly practices that also support climate resilience and biodiversity (SDG 15) (Preechapanya et al., 2021). By promoting fair trade, certification systems, and stronger smallholder cooperatives, the natural rubber industry can further contribute to decent work (SDG 8) and inclusive growth. The ongoing transformation in rubber production highlights the industry's role not only in meeting global market demands but also in achieving a sustainable, equitable, and environmentally responsible supply chain.

Ultimately, understanding the complexity of natural rubber trade flows requires a comprehensive approach that considers economic, environmental, and social factors. Elements such as production levels, price volatility, and external influences such as climate and global economic growth significantly shape trade outcomes. Sitepu et al. (2016) argued that sustainable development planning must address these trade-offs, to align with the UN's SDGs. By fostering economic growth, reducing environmental degradation, and promoting social equity, the natural rubber industry can move towards greater sustainability.

6. CONCLUSION

This study quantitatively analyzes the impacts of key factors associated with natural rubber trade flows in accordance with the UN's SDGs. The results of this study indicate that natural rubber harvest area, producer price, agricultural support, and annual mean temperature have statistically significant impacts on natural rubber imports and exports. Specifically, an increase in natural rubber harvest area results in increased natural rubber imports and exports. Higher producer price reduces natural rubber export volume, but increases import volume. Conversely, increased domestic agricultural support stabilizes domestic markets and reduces natural rubber imports and exports. Temperature increase adversely affects natural rubber imports and exports, while fertilizer consumption does not exert a significant impact on natural rubber trade volume. Lastly, global GDP showed no significant effect on natural rubber imports and exports. These findings underscore the significance of production levels, harvest area, producer price, and agricultural support, as well as other external factors such as climate change, in shaping the flow of natural rubber trade. They offer crucial insights for the development of sustainable trade and production policies.

Despite the fixed effects model effectively controlling for unobserved differences among countries, there is still a concern regarding the potential endogeneity of key independent variables, such as natural rubber harvest area, producer price, and agricultural support. Endogeneity may introduce bias into the estimated coefficients due to reverse causality or omitted variables that vary over time. While fixed effects control for time-invariant factors, they may not fully address these endogeneity concerns.

To address the potential biases introduced by endogeneity, future research could utilize instrumental variables (IV) or lagged independent variables as instruments. For example, historical weather data could be used as an instrument for natural rubber production, to establish the causal impact of these variables on trade flows. Additionally, employing separate models for net importer and net exporter countries could be used as robustness checks, as the inclusion of country fixed effects may overlook the time-invariant nature of countries that never produce or export natural rubber. This approach would provide a more comprehensive understanding of the factors influencing global trade flows for natural rubber.

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APPENDIX

Table 1A. The UN's 17 SDGs and their corresponding descriptions (source: UNDP)

SDG	Description
SDG 1: No Poverty	End poverty in all its forms everywhere.
SDG 2: Zero Hunger	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
SDG 3: Good Health and Well-being	Ensure healthy lives and promote well-being for all at all ages.
SDG 4: Quality Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
SDG 5: Gender Equality	Achieve gender equality and empower all women and girls.
SDG 6: Clean Water and Sanitation	Ensure availability and sustainable management of water and sanitation for all.
SDG 7: Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all.
SDG 8: Decent Work and Economic Growth	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.
SDG 9: Industry, Innovation, and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
SDG 10: Reduced Inequality	Reduce inequality within and among countries.
SDG 11: Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient, and sustainable.
SDG 12: Responsible Consumption and Production	Ensure sustainable consumption and production patterns.
SDG 13: Climate Action	Take urgent action to combat climate change and its impacts.
SDG 14: Life Below Water	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.
SDG 15: Life on Land	Protect, restore, and promote sustainable use of terrestrial ecosystems, manage forests sustainably, combat desertification, halt and reverse land degradation, and halt biodiversity loss.
SDG 16: Peace, Justice, and Strong Institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels.
SDG 17: Partnerships for the Goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development.