

INFRARED AND HOT-AIR DRYING OF STR20 RUBBER: ENHANCED EFFICIENCY AND QUALITY THROUGH ADVANCED MODELING

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Abstract

This study investigates the drying kinetics and quality characteristics of Standard Thai Rubber (STR20) using a novel infrared-hot-air drying system. The system was designed to automate temperature and moisture control for three grades of STR20, representing alternative ratios of natural cup lump rubber to smoked natural rubber sheet. Seven mathematical models were evaluated for best fit to the drying data, with the Logarithmic and Approximate Diffusion models showing the highest accuracy. Results demonstrated that infrared-hot-air drying achieved efficient energy consumption (average SEC of 25.82 MJ/kg), while preserving desirable rubber properties such as initial plasticity, plasticity retention index, viscosity, and volatile matter content within industry standards. These findings suggest that infrared-assisted drying can improve drying efficiency and product quality, offering an effective alternative for the rubber industry.

Keywords: Standard Thai Rubber (STR20); Infrared drying; Hybrid drying; and Drying kinetics

Introduction

Southeast Asia, particularly the ASEAN region, is ideal for cultivating the rubber tree (*Hevea brasiliensis*) due to its tropical climate. Rubber production is concentrated in Indonesia, Thailand, and Malaysia, which collectively account for 60% of the world's rubber-growing area. Natural rubber is a crucial export for ASEAN economies, significantly contributing to the region's economic stability. Natural rubber from Thailand is a vital raw material for multiple industries, including automotive tires, seals, couplings, footwear, molded goods, gloves, and medical devices. Currently,

Thailand's rubber supply chain plays a critical role in the global market, producing around 5.1 million tons annually. About 90% of this supply is derived from fresh latex, with the remainder coming from dry sources like cup lumps and rubber scraps. Block rubber, particularly Technically Specified Rubber (TSR) such as Standard Thai Rubber (STR) 20, constitutes 38.6% of Thailand's intermediate rubber output, much of which is exported to China and other markets for use in tires and durable rubber goods (Khongchana *et al.*, 2007; Sowcharoensuk, 2023). Overall, Thailand's rubber sector depends

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heavily on international markets, with nearly 81% of its intermediate rubber products destined for export.

Drying is essential for preserving agricultural products, as moisture promotes microbial spoilage and degradation. Traditional drying uses energy to heat and evaporate moisture, which is then removed by convection. While solar drying is the oldest method, it relies on favorable weather and is time-consuming. To address these limitations, modern drying methods, like infrared combined with hot-air drying, are widely used in industries such as textiles (Lee *et al.*, 2002), foods (Bhattacharjee *et al.*, 2024; Guo *et al.*, 2024), and rubber (Ortiz-Rodríguez *et al.*, 2021). Infrared radiation penetrates and excites water molecules within the product, providing efficient internal heating and enabling faster drying rates, improved heat transfer, and reduced energy costs. This efficiency has led to significant interest in infrared drying for agricultural and biological materials. Studies have shown that infrared can enhance drying kinetics, as with Murta berries (Puente-Díaz *et al.*, 2013), and even alter structures in natural rubber vulcanizates, affecting molecular bonds (Linnig and Stewart, 1958). In a previous study, Pianroj *et al.* (Pianroj *et al.*, 2018) studied infrared (IR) combined with hot-air for drying a natural crepe rubber sheet at the alternative drying temperatures 40, 50, and 60 °C. They reported that drying at 50 °C gave good rubber properties, and infrared (IR) assisted the shift in double and conjugated double bond crosslinks. Khongchana *et al.* (Khongchana *et al.*, 2007) investigated the effects of drying scenarios on the quality and energy consumption of STR20 rubber, and they found that the rubber dried at 130 °C for 40 min, followed by drying at 110 °C for a 120 min drying time had better quality and the lowest specific energy consumption (SEC). Ng *et al.* (Ng *et al.*, 2015) studied crumb rubber drying in different experimental designs. They found the energy consumption for vacuum drying was higher than that of hot-air drying at the same 100 °C drying temperature, and the best-fit model was the modified Henderson and Pabis model. Korkua *et al.* (Korkua *et al.*, 2022) proposed the potential in natural rubber drying of using microwave technology powered by solar energy, to reduce the carbon dioxide emissions below those of traditional drying methods.

Therefore, in this study, an infrared radiation with hot-air drying system was designed and built to automatically collect data for a study of the drying kinetics, conditional on alternative STR20 rubber sample grades. Seven mathematical models were

used to fit the drying data, and then the samples of dried STR20 were characterized to compare with Standard Thai Rubber in terms of the parameters initial plasticity (Po), plasticity retention index, Mooney viscosity (MV), volatile matter (VM), and specific energy consumption.

Materials and Methods

Materials and Experimental Set-up

STR20 is a major product for rubber manufacturers and exporters in Thailand. It is a blend of natural cup lump rubber (NCLR) and smoked natural rubber sheet (SNRS) in standardized ratios. This product is classified into three grades based on the NCLR-to-SNRS ratio: grade 5 (STR20-G5) at 35:65, grade 6 (STR20-G6) at 50:50, and grade 7 (STR20-G7) at 65:35. In this study, STR20 samples were provided by Y.T. Rubber Co., Ltd. (YTRC) in Surat Thani. Each sample, weighing 2,000 grams, was placed in a stainless-steel mesh basket measuring 33×67×18 cm and suspended in a custom-built infrared drying chamber with dimensions of 120×120×90 cm. The chamber walls were constructed from zinc-coated metal with thermal insulation, designed to reflect infrared radiation, maintain consistent temperatures, and reduce energy consumption. Six infrared tubes, each with a 1.7 cm diameter, 75 cm length, and 1,000 W power (SG-H model), were installed on the chamber's two side walls. Inside the chamber, temperature monitoring was performed using three thermocouples (T_1 , T_3 , and T_4) placed in the chamber and an additional thermocouple (T_2) was positioned inside the STR20 sample and it was connected to a temperature controller that regulated the system via a magnetic relay. In this study, the target temperature was set at 100 ± 20 °C. A digital balance, positioned on top of the chamber, had a maximum load capacity of 30 kg with an accuracy of ± 1.0 g. It was used to continuously record the real-time weight of the STR20 sample, which was suspended on a stainless-steel bar. The weight data were transmitted to a PC via an RS232 port for precise logging. To enhance air circulation within the chamber, a 10.2 cm diameter ventilation fan was installed at an exhaust vent on the side wall, while a 20.3 cm diameter electric heater and blower served as the intake vent on the bottom wall. Finally, the whole system was connected to a kilowatt-hour meter to measure electricity consumption in each drying experiment. A detailed schematic of the infrared-convection drying system is shown in Figure 1.

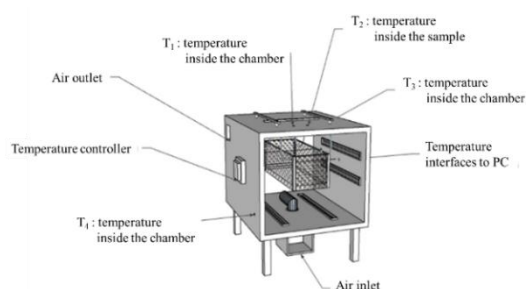


Figure 1. A schematic diagram of the IR with convection system for drying STR20. Note that thermocouples T₁, T₃, and T₄ monitored chamber temperature, and the thermocouple T₂ monitored temperature inside the STR20 sample

Methods

The STR20-G5, STR20-G6, and STR20-G7 samples each weighing 2,000 g were dried by using the hybrid system that combined infrared (IR) at 6,000 W and convection with airflow speed 3.4 m/s, temperature target inside samples at 105 °C, and drying time at 120 min. After that, the heating system was closed, and the sample was left inside the chamber until the temperature inside matched the ambient temperature. Finally, a subsample of approximately 250-300 g was collected to characterize the Mooney viscosity (MV), the initial plasticity (Po), the plasticity retention index, the volatile matter content (VM), and the specific energy consumption (SEC). It should be noted that the heating pattern employed in this study was selected based on industrial relevance, product quality preservation, and process controllability for STR20 rubber drying. In industrial block rubber

production, drying is typically conducted at moderate temperatures (approximately 100-130 °C) to ensure effective moisture removal while maintaining acceptable plasticity and aging resistance. Accordingly, the present study adopted a controlled infrared-hot-air hybrid heating pattern with target air temperatures within this industrially relevant range, combined with continuous

monitoring of the internal sample temperature to avoid localized overheating. Unlike several previous studies that applied fixed high-temperature hot-air profiles or stepwise heating schedules primarily focused on drying rate enhancement, the current approach emphasizes uniform heat distribution and stable internal temperature control under automated operation. Infrared radiation was introduced as a supplementary heat source to enhance surface evaporation and heat transfer efficiency, while forced hot-air convection ensured moisture removal from the rubber matrix. This heating strategy differs from earlier profiles reported in the literature by prioritizing process stability and quality consistency for STR20 grades rather than solely maximizing drying speed.

Results and Discussion

Physical properties after drying and temperature profiles

The physical properties of the STR20 sample, observed visually before and after the drying, are presented in Figure 2. The sample exhibited a uniform yellow-brown color without visible white spots, which indicates that the STR20 is sufficiently dried and free from residual surface moisture. The temperature profiles for the infrared and hot-air drying system are shown in Figure 3. Thermocouples T₁, T₃, and T₄ tracked chamber temperature, illustrating the heating performance. A rapid temperature rise occurred from 0 to 20 minutes, reaching the target range of 100±20°C from room temperature. Meanwhile, thermocouple T₂ monitored the internal temperature of the STR20 sample, which required approximately 80 minutes to reach the set temperature due to the temperature gradient between the chamber and sample interior, along with radiative heat transfer. Following this, temperature equilibrium was maintained inside and outside the sample until the drying process concluded, managed by the temperature controller and ON-OFF magnetic relay.



Figure 2. Visual comparison of STR20 physical properties: the top panel shows the raw STR20 sample, while the middle and bottom panels display the cured STR20 sample after drying

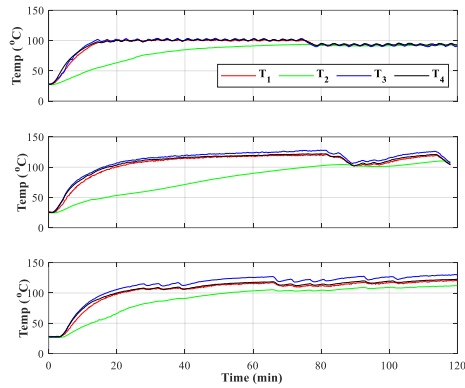


Figure 3. Temperature profiles for STR20-G5, STR20-G6, and STR20-G7 are displayed in this order from top to bottom panels. Thermocouples T₁, T₃, and T₄ monitor chamber temperature, while T₂ tracks temperature within the sample

Mathematical Modeling

To model the moisture ratio data for STR20 samples of grades 5, 6, and 7, seven alternative models were evaluated, as presented in Table 1. Each model's fit quality was assessed using the coefficient of determination (R^2) and the root mean square error ($RMSE$). Experimental moisture ratio data were normalized by calculating the ratio of moisture at time (t) to the initial moisture level for the STR20 sample. In general, R^2 describes how much of the variance in experimental moisture ratio is explained by the model (values closer to 1 indicate a stronger explanation), while $RMSE$ quantifies the typical deviation between predicted and observed values (smaller $RMSE$ indicates lower prediction error). Therefore, models with higher R^2 and lower $RMSE$ provide better agreement with experimental data.

To compare the drying behavior across grades of STR20, moisture contents were normalized, revealing similar drying trends and an increase in drying rate with higher controlled temperatures. During the initial 20 minutes, moisture reduction was rapid due to surface water evaporation,

followed by a slower drying phase caused by the sample's thickness and internal diffusion resistance as shown in Figure 4. The fit quality of the seven mathematical models to experimental data is presented in Table 2. Results indicate that the Logarithmic and Approximate Diffusion models provided the best fit for STR20-G5, STR20-G6, and STR20-G7, with high R^2 values and low $RMSE$ values of 0.964; 0.034, 0.942; 0.036, and 0.954; 0.039, respectively.

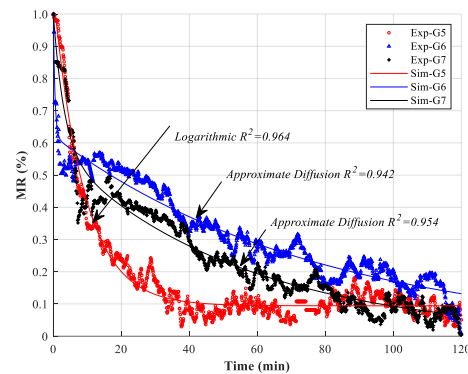


Figure 4. Moisture ratio versus drying time: comparison of experimental and simulated data for each grade of STR20

Properties of Dried STR20

This experiment evaluates STR20 plasticity properties through two key indicators: initial plasticity (P_o) and plasticity retention index, with average values across $n = 9$ replicates for each grade shown in Figure 5. P_o estimates rubber's molecular size, reflecting the ease of processing. Higher P_o , linked to a high molecular weight, indicates greater viscosity, requiring more energy and time for milling but resulting in superior mechanical properties. For STR20, a minimum P_o of 30 is required; on the other hand, PRI measures resistance to oxidation at 140°C for 30 minutes, indicating the rubber's durability under heat. STR20's PRI must meet or exceed 40%. Experimental P_o and PRI values for the three grades of STR20 (Figure 5) range within 42.07-44.24 and 69.99-84.72,

Table 1. The seven mathematical models tried for curve fitting

No.	Name of model	Expression of model	Reference
1	Henderson and Pabis	$MR = a \cdot \exp(-kt)$	(Henderson and Pabis, 1961)
2	Page	$MR = \exp(-kt^n)$	(Page, 1949)
3	Logarithmic	$MR = a \cdot \exp(-kt) + c$	(Yaldiz <i>et al.</i> , 2001)
4	Approximation of Diffusion	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-kbt)$	(Yaldiz <i>et al.</i> , 2001)
5	Modified Henderson and Pabis	$MR = a \cdot \exp(-kt) + b \cdot \exp(-gt) + c \cdot \exp(-ht)$	(Karathanos and Belessiotis, 1999)
6	Midilli	$MR = a \cdot \exp(-kt^n) + bt$	(Midilli <i>et al.</i> , 2002)
7	Modified quasi-stationary method	$MR = \frac{1}{(1 + (t/s)^n)}$	(Tsotsas and Mujumdar, 2007)

Table 2. Goodness-of-fit results for each candidate model across different grades of STR20

Model	STR20-G5			STR20-G6			STR20-G7		
	R^2	RMSE	constants	R^2	RMSE	constants	R^2	RMSE	constants
Henderson and Pabis	0.795	0.080	a = 0.902 k = 0.064	0.926	0.041	a = 0.635 k = 0.013	0.904	0.056	a = 0.690 k = 0.022
Page	0.870	0.064	k = 0.224 n = 0.589	0.851	0.058	k = 0.216 n = 0.437	0.931	0.048	k = 0.173 n = 0.556
Logarithmic	0.964	0.034	a = 0.970 k = 0.111 c = 0.094	0.923	0.041	a = 0.669 k = 0.042 c = -0.042	0.908	0.055	a = 0.671 k = 0.027 c = 0.049
Approximate Diffusion	0.956	0.037	a = 0.077 k = 5.594e-5 b = 1723	0.942	0.036	a = 0.378 k = 2.174 b = 0.006	0.954	0.039	a = 0.417 k = 0.316 b = 0.058
Modified Henderson and Pabis	0.780	0.083	a = 0.942 b = 264.2 c = -263.6 g = 1.488 h = 1.487 k = -0.068	0.804	0.066	a = 0.478 b = 0.790 c = -1.027e-12 g = 0.728 h = -0.212 k = 0.009	0.851	0.0701	a = 412.4 b = 0.708 c = -411.4 g = 0.022 h = 0.243 k = 0.244
Midilli	0.961	0.035	a = 1.166 b = 9.611e-4 k = 0.187 n = 0.750	0.927	0.041	a = 0.6087 b = 2.786e-4 k = 6.432e-3 n = 1.183	0.943	0.043	a = 1.201 b = -0.001 k = 0.3637 n = 0.349
Modified Quasi-stationary method	0.929	0.047	a = 7.272 n = 1.116	0.799	0.067	a = 13.000 n = 0.636	0.901	0.055	a = 11.350 n = 0.890

respectively, surpassing standard criteria. STR20-G5 showed higher P_o and PRI values than STR20-G6 and STR20-G7, suggesting that longer storage may enhance these values due to physical cross-linking and limited chemical interactions of rubber chains during storage or drying. In natural rubber, molecular terminals play a role in forming branch points through protein and phospholipid bonds, potentially allowing for cross-linking and strengthening of the rubber chains (Pianroj et al., 2018).

A one-way analysis of variance (ANOVA) was conducted in MS Excel using the Analysis ToolPak add-in to test whether the group means were statistically similar across all samples. A confidence level of 95% was used, meaning a p -value < 0.05 would reject the null hypothesis (H_0). The hypotheses were set as follows: H_0 : The mean P_o and PRI values are the same across each STR20 rubber grade, and H_1 : The mean P_o and PRI values differ among the grades. The ANOVA results showed p -values of 0.022 for P_o and $6.100e^{-6}$ for PRI, both of which are less than 0.05. This indicates a rejection of H_0 and acceptance of H_1 , meaning that the mean P_o and PRI values are significantly different between each grade of STR20. These differences are likely due to the alternative ratios of natural cup lump rubber to smoked natural rubber sheets in the raw material blends.

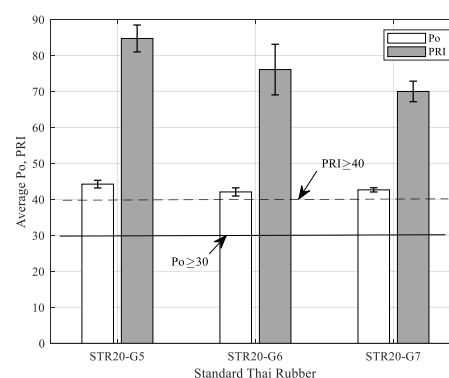


Figure 5. The average initial plasticity (P_o), and the average plasticity retention index (PRI) of each grade of STR20 rubber type tested

Mooney Viscosity (MV), Volatile Matter (VM), and Specific Energy Consumption (SEC)

Viscosity reflects the molecular weight of rubber and indicates the resilience of rubber trees, with older trees typically producing higher-viscosity latex. Latex nearing the end of the tree's tapping cycle or from younger trees usually has lower viscosity. Rubber varieties with higher molecular weights also show elevated viscosity values. Viscosity is measured with a Mooney Viscometer, which operates by placing rubber in a chamber with a rotating disc under controlled temperature and

pressure. This rotation creates torque, moving a U-shaped spring, and a micrometer records this movement as the value in Mooney units. The top panel of Figure 6 presents viscosity test results for STR20 grades, with one sample tested per grade. In the MV testing, the hypotheses were set: H_0 : The mean MV value is the same across each STR20 rubber grade, and H_1 : The mean MV value differs among the grades. The p -value of 0.009 emerged for MV, which is less than 0.05, indicating rejection of H_0 and acceptance of H_1 , meaning that the mean MV significantly differs by grade of STR20 rubber. The results show that STR20-G5, STR20-G6, and STR20-G7 have viscosity values of 77.08%, 81.46%, and 83.46%, respectively, all meeting block rubber standards (80 ± 10). STR20-G7 displayed the highest viscosity among the grades, attributed to the largest fraction of thicker cup lump rubber in block rubber processing. Cup lump rubber experiences less molecular chain breakage than raw rubber sheets, resulting in a higher molecular weight and, therefore, a greater viscosity. Consequently, STR20-G7 exhibits higher viscosity than STR20-G5 and STR20-G6 due to its higher proportion of cup lump rubber relative to raw rubber sheets.

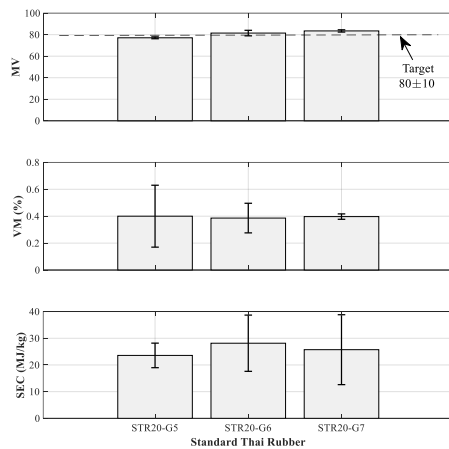


Figure 6. Mooney viscosity (MV), volatile matter content (VM), and specific energy consumption (SEC) for STR20-G5, STR20-G6, and STR20-G7 are shown in the top, middle, and bottom panels, in this order

Volatile matter content (VM) in rubber refers to its moisture content. High moisture levels make rubber more susceptible to mold growth, unpleasant odors, and complications during processing into final products. In block rubber production, steps like rolling, cutting, and cleaning are used to prepare the rubber. The rubber is cut into small pieces, dried, and packaged, resulting in a lower VM compared to raw rubber. The middle panel of Fig. 6 displays the

VM test results for each grade, showing that STR20-G5, STR20-G6, and STR20-G7 have VM contents of 0.40%, 0.39%, and 0.40%, respectively. All three grades meet the Standard Thai Rubber requirement, which specifies a VM content of no more than 0.80%. Statistically, the volatile matter content is consistent across all three grades; after the hypothesis testing, the p -value was $0.993 \geq 0.05$. It can be concluded that the mean VM does not differ significantly across STR20 grades.

The specific energy consumption (SEC) represents the amount of energy needed to process or dry a unit mass of material. In this study, it reflects the combined effect of infrared radiation and forced hot-air convection. While the obtained SEC values suggest efficient moisture removal, it should be emphasized that these values cannot be directly interpreted as an improvement over conventional hot-air drying without a controlled baseline experiment. Nevertheless, comparison with previously published data provides useful context, suggesting that infrared-assisted drying has the potential to reduce drying time and energy demand through enhanced heat transfer and surface evaporation.

The bottom panel of Figure 6 presents the drying results for rubber using 6,000 Watts of energy and a temperature range of 80–120 °C over a 2-hour drying period. SEC values for STR20-G5, STR20-G6, and STR20-G7 were 23.58 MJ/kg, 28.15 MJ/kg, and 25.73 MJ/kg, respectively. To examine whether SEC values differed significantly among the grades, a hypothesis test was conducted. The null hypothesis (H_0) stated that the mean SEC is the same across all STR20 grades, while the alternative hypothesis (H_1) proposed that the mean SEC differs between grades. With a p -value of 0.514 (greater than 0.05), it fails to reject H_0 , concluding that the mean SEC value does not differ significantly across STR20 grades. However, the SEC results from this study show an average of 25.82 MJ/kg. Although a direct experimental comparison with conventional hot-air drying under identical operating conditions was not conducted in the present study, the drying performance of the infrared-hot-air hybrid system can be contextualized by comparison with values reported in the literature. Previous studies on conventional hot-air drying of natural rubber and STR-grade rubbers typically report longer drying times and specific energy consumption (SEC) values ranging from 26.09–29.52 MJ/kg, depending on temperature, airflow, and sample geometry (Khongchana *et al.*, 2007). In the present work, the measured drying time and SEC values obtained using the infrared-hot-air system fall within or below the lower range of these reported values, indicating that the hybrid system

provides competitive drying performance. However, because drying kinetics and energy consumption are strongly influenced by system configuration and operating parameters, a controlled side-by-side comparison is required to quantitatively determine the extent of improvement attributable to infrared assistance.

It should be noted that a direct experimental comparison with conventional hot-air drying under identical conditions was not performed in this study. Future work will focus on a controlled comparative investigation to quantitatively assess the advantages of infrared-assisted drying in terms of drying kinetics, energy efficiency, and product quality.

Conclusions

This study successfully designed and implemented an infrared and hot-air drying system to explore the drying kinetics of Standard Thai Rubber (STR20). From evaluating three grades of STR20, it can be observed that the infrared-hot-air system provided effective and consistent drying, achieving an average specific energy consumption (SEC) of 25.82 MJ/kg. The findings indicate that this combined drying approach enhances efficiency while maintaining desirable properties such as plasticity, viscosity, and volatile matter content, all within the Standard Thai Rubber criteria. Furthermore, the selected mathematical models demonstrated a high level of accuracy in fitting the drying curves across all grades, with the Logarithmic and Approximate Diffusion models yielding the best results. This research highlights the potential of infrared and hot-air drying to optimize energy use and improve the quality of block rubber, offering a valuable method for rubber production applications.

This study aligns with the United Nations SDGs, particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production), by promoting innovative, energy-saving methods in rubber production. Studies confirm the benefits of infrared drying for agricultural products, such as berries and rubber vulcanizates, where it has been shown to improve drying kinetics and even alter molecular structures to enhance quality. Moreover, this study approach not only supports advances in rubber drying technology but also aligns with SDG 7 (Affordable and Clean Energy) by exploring solutions that reduce energy use in agricultural processing, thus contributing to a more sustainable rubber industry.

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Author Contributions

Saysunee Jumrat: Methodology, Data Collection, and Writing-Original Draft.; **Saranyoo Klaiklay:** Data Collection, and Formal Analysis.; **Jirapond Muangprathub:** Data Collection, and Validation.; **Seppo Karrila:** Writing-Review&Editing.; **Yutthapong Pianroj:** Conceptualization, Methodology, Writing-Review&Editing, and Supervision.

Ethics Approval and Consent to Participate

The research was strictly limited to laboratory-scale physical experiments evaluating the drying kinetics and physical properties of Standard Thai Rubber (STR20) blends, alongside mathematical and statistical curve-fitting. This work did not involve human participants, live animals, or biological tissue samples.

Declaration of Generative AI

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

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