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Prediction of Size Distribution and Mass Concentration of Smoke Particles on Moisture Content and Combustion Period from Para Rubber Wood Burning

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Abstract: The size distribution and total particle mass concentration (*TPMC*) of smoke particles from para rubber wood (*Hevea brasiliensis*) combustion in the ribbed smoked sheet (RSS) process were studied. In this experiment, temperature data values of para rubber wood combustion were recorded at 500 mm above the base of the fire by K-type thermocouples. The wood moisture content and wood combustion period were used to find and improve an equation of smoke particle size distribution (SPSD) and *TPMC* by the response surface method (RSM). An eight-stage Andersen air sampler and a high-volume sampler were used to measure and calculate SPSPD and *TPMC*, respectively. Resulting data in this experiment showed that *TPMC* ranged from 3.12 to 77.42 mg/m³. SPSPD was single mode in which *MMAD*, mass median aerodynamic diameter, ranged from 0.64 to 1.27 microns for para wood with moisture content ranging from 31.5 to 89.7% dry weight basis. The combustion period and moisture content of para wood have a direct effect on the change of temperature data above the base of the fire and the *TPMC* and *MMAD* values. For predicting *TPMC* and *MMAD* values by the para wood moisture contents in each combustion period, the results found that the second-degree model was a better plot than the first-degree model, confirmed by higher values of the coefficient of determination (R^2).

Keywords: response surface; para rubber wood; *MMAD*; size distribution; prediction



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1. Introduction

Currently, biomass is the most important source of renewable energy in the world [1–3]. Particularly in the south of Thailand, para rubber wood (*Hevea brasiliensis*) has been popular for use both in the community and industry. Exhaust from the wood combustion contains water vapor and gases, including CO₂, CO, and N₂; soot particles; smoke; and ash residue [4,5]. As the moisture content of the wood is increased, the water vapor present rises. Smoke and soot are composed of the small particles resulting incomplete combustion. The small particles principally contain carbon and other combustible materials: for instance, polycyclic aromatic hydrocarbons or PAHs [6,7], tar, and volatile [8–11]. In the drying process of ribbed smoked sheet (RSS) production, hazardous air pollutants from para rubber wood combustion, such as smoke particles, cause worker and neighborhood health problems. In addition, smoke particles from para rubber wood burning has a negative effect on the quality of RSS [12,13] and thus lowers the price. In order to manage the smoke particles appropriately, a study of their characteristics was necessary.

Many researchers [14–17] have studied smoke and soot particle characteristics. The report of Chomanee et al. [18] is the only study on the mass concentration of smoke particles from para rubber wood combustion under different moisture contents (37.4%, 69.8%, and 73.6% dry weight basis (d.b.)) and burning time periods.

The reports by Chomanee et al. [18] and Kalasee et al. [1] showed that the condensation in an eight-stage Andersen air sampler had a direct effect on the *MMAD* of para rubber

wood combustion. Increased water vapor condensation increased the *MMAD* value. Currently, there has been no research studying aerosol and smoke particles parameters and predicting the effect of the influence of parameters on *TPMC* and *MMAD* values from para rubber wood burning.

Therefore, the purpose of this research was to study and predict the change of *TPMC* and *MMAD* values, which is related to para rubber wood moisture content value, time periods of combustion, and temperature values above the base of the fire. This study would be useful for solving environmental workplace problems and worker risk in the future.

2. Materials and Methods

This section clarifies the methods used to merge, consider, and analyze smoke particle samples from a burner. Figure 1 shows the burner that was used to study *TPMC* and *MMAD* values of para rubber wood combustion.

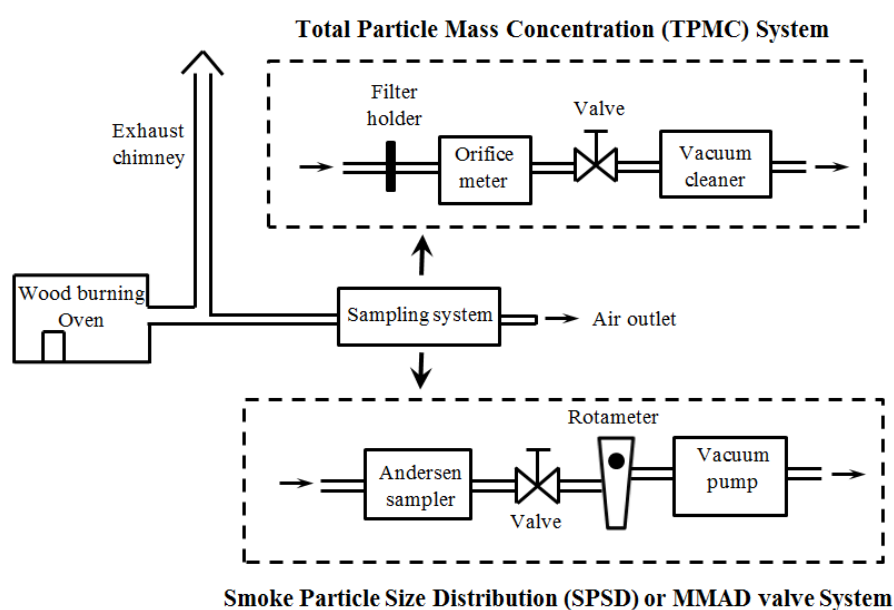


Figure 1. Schematic diagram of smoke particle sampling methods for *TPMC* and *MMAD* value calculation.

2.1. Biomass Fuel Used

The twenty-five-year-old [14,19] para rubber wood used as fuel in this study was from the Agriculture, Food, and Energy Center, King Mongkut's Institute of Technology Ladkrabang, Prince of Chumphon Campus, Chumphon, Thailand, with an initial moisture content from 31.5% to 89.7% d.b. To determine the moisture content of the wood samples, 5-piece samplers were placed in positions next to the wood log front, middle, back, between front and middle, and between middle and back, respectively; they were weighed and put on aluminum trays for moisture content determination (AOAC, 2005) in an electric air oven (Mammert, 400) at 103 °C until a constant weight was obtained [1,13,17].

2.2. Sampling Methods

In the experiment, 145 logs of para rubber wood samples were randomly taken from the Agriculture, Food, and Energy Center. The length, weight, and moisture content of all samples were measured and recorded. Dependent on the wood samples' initial average moisture condition, they were divided into five groups of 31.5, 35.4, 42.5, 54.8, and 89.7% d.b. Every experimental group for the samples was repeated five times. The wood samples (25 kg or about 5–6 logs of wood) for every experiment were burned in a burner constructed from bricks and mortar, with dimensions of 0.5 × 0.7 × 1.5 m. During combustion, the wood samples, having a length of about 0.50 m, were fed into the furnace by placing them

at the base of the oven. Air flows into the burner via a gap in the bottom of the furnace gate. Source smoke and soot particles from the furnace were sampled by two groups of an apparatus to determine *TPMC* and *MMAD* values (Figure 1). Thus, the 250 data (5 run $\times$ 10 time $\times$ 5 repeat) were used for the construction of the models.

2.3. Temperature Data Value Recording

The temperature data values of the para rubber wood combustion were recorded at 500 mm above the base of the fire by using K-type thermocouples and a data logger (Data-Taker, DT500). The data logger recorded the temperatures at 1-min intervals to ensure a continuous reading. The temperature data for analyses was considered after the para rubber wood was burned for 15, 30, 60, 75, 120, 135, 150, and 165 min, respectively.

2.4. Particles Size Distribution

Size distribution of the smoke particles and the geometric standard deviation (*GSD*) value from para rubber wood combustion were determined by collecting particles using an 8-stage Andersen air sampler [Dylec, AN200]. This sampler had cut sizes of 0.43, 0.65, 1.1, 2.1, 3.3, 4.7, 7.0, and 11.0 microns. A backup filter was placed on the bottom stage of the sampler; it was used to collect smoke particles which had dimensions of less than 0.43 microns. The sampling flow rate was set at 28.3 lpm by the flow experiment set control (Figure 1). An 80-m diameter of quartz-type fibrous filter [ADVENTEC, QR-100] was placed on a glass plate and used to collect smoke particles at each stage of the air sampler. The sampling gas temperature ranged between 100 and 200 °C; therefore, the Andersen impactors and tubing were insulated with glass fiber to prevent condensation. This sampling tube had a length of 3.0 m. The gas temperature decreased by less than 50 °C before entering the air sampler, preventing system condensation. The smoke particle size distribution was measured after the para rubber wood had burned for 15, 30, 60, 75, 120, 135, and 150 min, and each sampling was taken over 10 min. The *MMAD* value was defined as the aerodynamic diameter at 50% of the cumulative oversize percentage of the smoke particles, and the *GSD* value of the smoke particles was written as [20]

$$GSD = \frac{d_{84.1\%}}{d_{50\%}} = \frac{d_{50\%}}{d_{15.9\%}} \quad (1)$$

2.5. Total Smoke Particle Mass Concentration

The total particle mass concentration (*TPMC*) of smoke particles from para rubber wood combustion was determined by collecting particles using a vacuum air sampler [Daikawa, 2VP-120L]. A quartz-type fibrous filter [ADVENTEC, QR-100] having a diameter of 110 mm was placed in the filter holder. The sampling flow rate was set at 100 lpm by the flow experiment set control (Figure 1). The relationship between *TPMC* and time periods was determined and measured under the same conditions as the smoke particle size distribution.

2.6. Modelling by Response Surface Method

RSM or the response surface method was a technique for learning the relationship between a response of interest (*y*) and input parameters (*x*). For an equation to predict *MMAD* and *TPMC* value changes during para rubber wood burning, wood moisture content (*MR*) and drying time (*t*) would be the input variables. Thus, the functions were specified by Equation (2) for *MMAD* and *TPMC* values.

$$MMAD \text{ or } TPMC = F(MR, t) \quad (2)$$

It is agreeable to assume the random experimental error value was zero. The first- and second-degree prediction models of *MMAD* and *TPMC* value changes could be written as follows:

The first-degree prediction models could be calculated from

$$MMAD \text{ or } TPMC = p_0 + p_1MR + p_2t \quad (3)$$

The second degree prediction models could be calculated from

$$MMAD \text{ or } TPMC = p_0 + p_1MR + p_2t + p_3MR^2 + p_4t^2 + p_5MRt \quad (4)$$

3. Results and Discussion

3.1. Temperature Variation

Figure 2 shows the results of the effect of the wood combustion period and the temperature data values above the base of the fire. Figure 2 illustrates that the para rubber wood combustion had three phases: preheating, degassing, and charcoal. It agrees with the results reported by [21–23], which studied the time and temperature combustion profiles of various woods, such as pine wood and eucalyptus wood. In the preheating phase, temperature values rose quickly from the initial combustion period to about 15–30 min after initial combustion. Temperature values increased with decreasing the moisture content. In the second phase (degassing), temperature values dropped during the first part, and the values increased during the second part after most of the tar and volatile particles dissolved [21,23–25]. Finally, at the charcoal phase, the temperature values decreased to 50–52 °C.

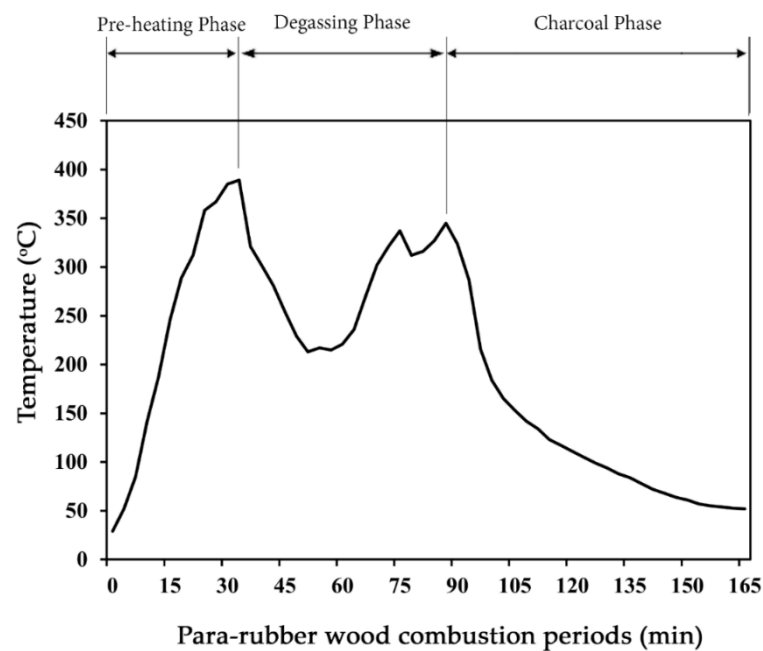


Figure 2. The phase change temperature in para rubber wood combustion.

Figure 3 illustrates that the para rubber wood moisture content had a prime influence on increasing temperature data values above the base of the fire. Thus, it shows the highest temperature value of about 475 °C was found at the lowest wood moisture content, 31.5% d.b., in the preheating phase. The wood combustion period in the degassing phase, 89.7% d.b., was the longest because 89.7% d.b. had the highest wood moisture content value and had the most tar and volatile particles [21–23]. In the charcoal phase, the results showed that 89.7% d.b. took the shortest time because it had the least heartwood after burning in the first and second phases of the wood combustion stages [21,24,25].

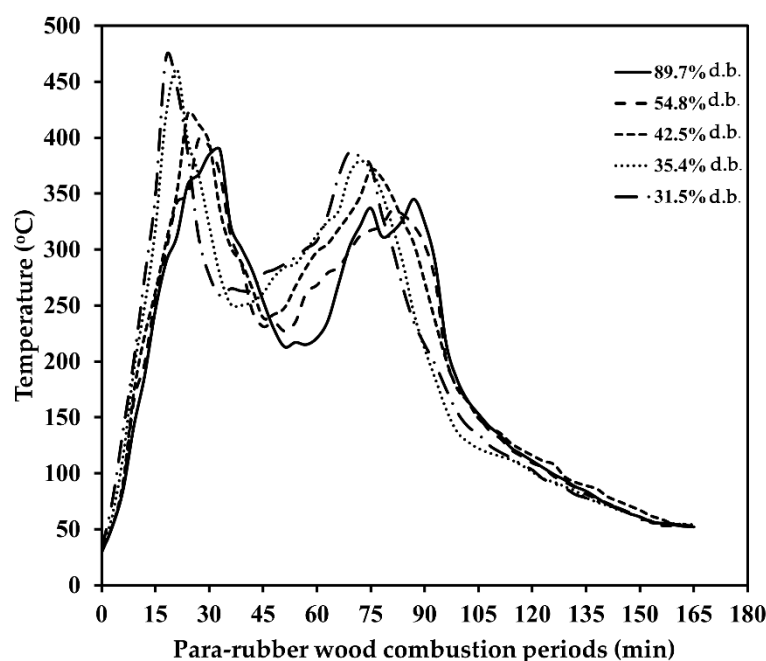


Figure 3. The temperature at 500 mm above the base of the fire for the different para rubber wood moisture contents.

3.2. Smoke Particle Size Distribution

Table 1 presents the comparison of the *MMAD* and *TPMC* value results, measured from a normal and modified eight-stage Andersen air sampler system. For the modified system, the Andersen impactors and tubing were insulated with glass fiber to prevent condensation, but for the normal system, these were not insulated. The results showed the *MMAD* value results measured from the modified system were less than the normal system by about 10–15%, but *TPMC* was not significantly different. For this reason, the modified system was improved to prevent its condensation.

Table 1. The comparison of *MMAD* and *TPMC* value results measured from a normal and modified 8-stage Andersen air sampler system.

Type of Andersen Air Sampler System	Moisture Content (% d.b.)	Burning Period (min)	<i>MMAD</i> (Micron)	<i>TPMC</i> (mg/m ³)
Normal	89.70%	15	1.37	79.28
		30	1.29	62.59
		45	0.91	49.14
Modified	89.70%	15	1.25	77.42
		30	1.16	61.51
		45	0.82	48.23

Figure 4 shows the effect of the wood combustion period and moisture content on the smoke particle distribution measurement results using an eight-stage Andersen sampler from five samples with moisture content varying from 31.5% to 89.7% d.b. The results showed that the increase in moisture content level had a strong influence on increasing smoke particle size distribution. The smoke particle size distribution indicated a single-mode behavior, suggesting that most of the particles were associated with small particles. This agreed with the results reported by [1,2,16,18,26].

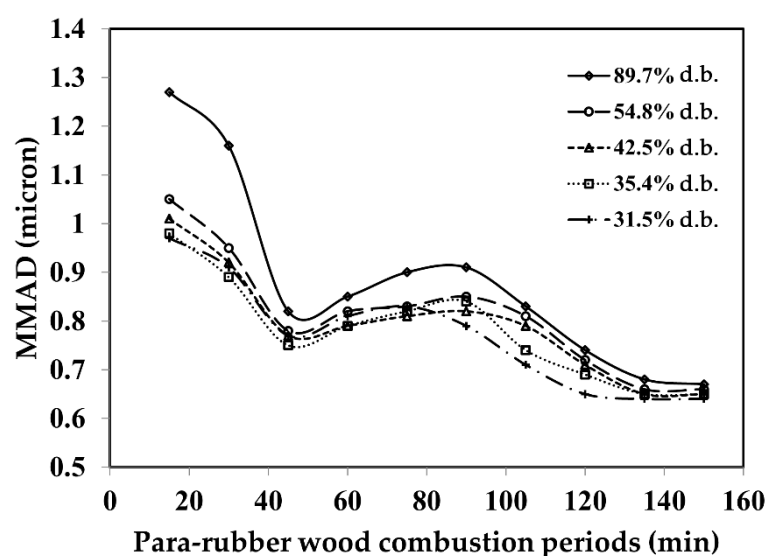


Figure 4. *MMAD* emission from the para rubber wood combustion for different wood moisture contents.

The mass median aerodynamic diameter (*MMAD*) values were found to be 0.62 to 1.27 microns throughout different wood burning periods and with different moisture contents, as shown in Figure 4. The highest *MMAD* values were found to be 0.97 to 1.25 microns at the initial combustion period, having the highest para rubber wood moisture content. As shown in Figure 4, at 89.7% d.b., the *MMAD* values decreased rapidly at 15 to 45 min after the wood's initial combustion. This result illustrated that the vapor from wood combustion caused the size of smoke particles to be larger than normal from addition and impaction. After 90 min, the *MMAD* values reduced to 0.79 to 0.91 microns. In the final period (after 150 min after initial combustion), *MMAD* values reduced to 0.64 to 0.67 microns. The results showed that the time increase had a high influence on decreasing the *MMAD* values because the degree of incomplete burning is decreased after the evaporation of the water in every type of wood [27–31], including para rubber wood in this experiment.

3.3. Total Particle Mass Concentration of the Smoke Particles

Figure 5 presents the results of total particle mass concentration (*TPMC*) of smoke particles from para rubber wood combustion. In the initial combustion period, *TPMC* values were found to be 31.25 to 77.42 mg/m³. After 90 min from initial combustion, the *TPMC* values reduced to 16.52 to 25.29 microns. In the final period (150 min after initial combustion), the *TPMC* values reduced to 3.12 to 7.21 microns. The results showed that the increase of time periods had a prime influence on decreasing the *TPMC* values, synonymous with the *MMAD* values.

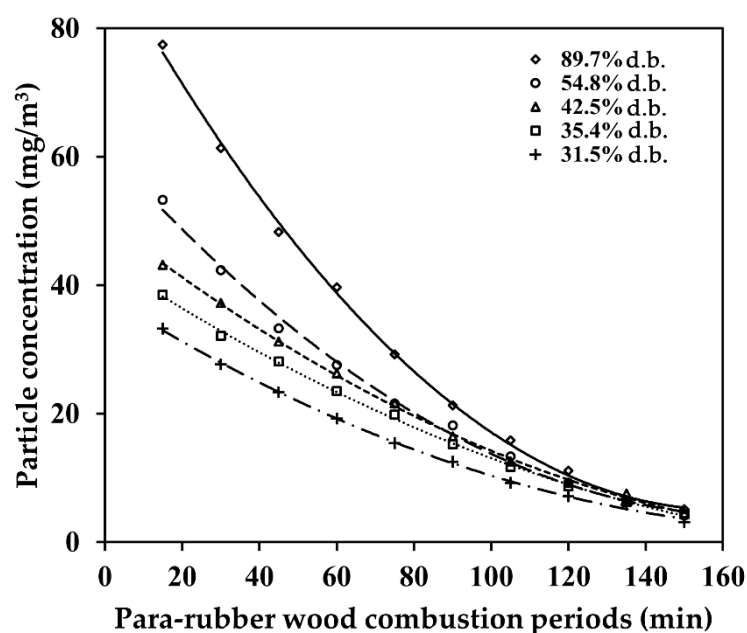


Figure 5. TPMC emission from the para rubber wood combustion for different wood moisture contents.

3.4. Prediction of MMAD Values Change

In order to fit a good model, the least-squares technique was used to calculate the coefficient values of the expressed rate constant at various combustion temperatures and orders. Figure 6a,b shows the MMAD values' 3D surface plots by the first- and second-degree models or Equations (3) and (4). The x -axis and y -axis present the para rubber wood moisture content and the burning time period, respectively, while the z -axis shows the MMAD values. These results show that the moisture content of para rubber wood affected the MMAD values when compared with the burning time. Table 2 presents the p coefficient values calculated by the least-squares method. As seen in Figure 6a,b, at the combustion period, the response of both models presents a decreased trend of MMAD values as the combustion time increases, although only the clear response of the second-degree model presented the effect of moisture content on decreasing the MMAD value as the combustion time progressed, relating to the results. Comparing the MMAD data between the experimental results and prediction values, the second-degree model had a better fit in predicting than the first-degree model; this result is confirmed by the higher mean of the coefficient of determination (Figure 7a,b), respectively. Although the second-degree model had a better fit in prediction than the first-degree model, the mean of the coefficient of determination, or R^2 , was 0.8267, which is a rather low value. It is probable that in the future, high (third, fourth, fifth, sixth) polynomial degree models will be a very interesting research method to study.

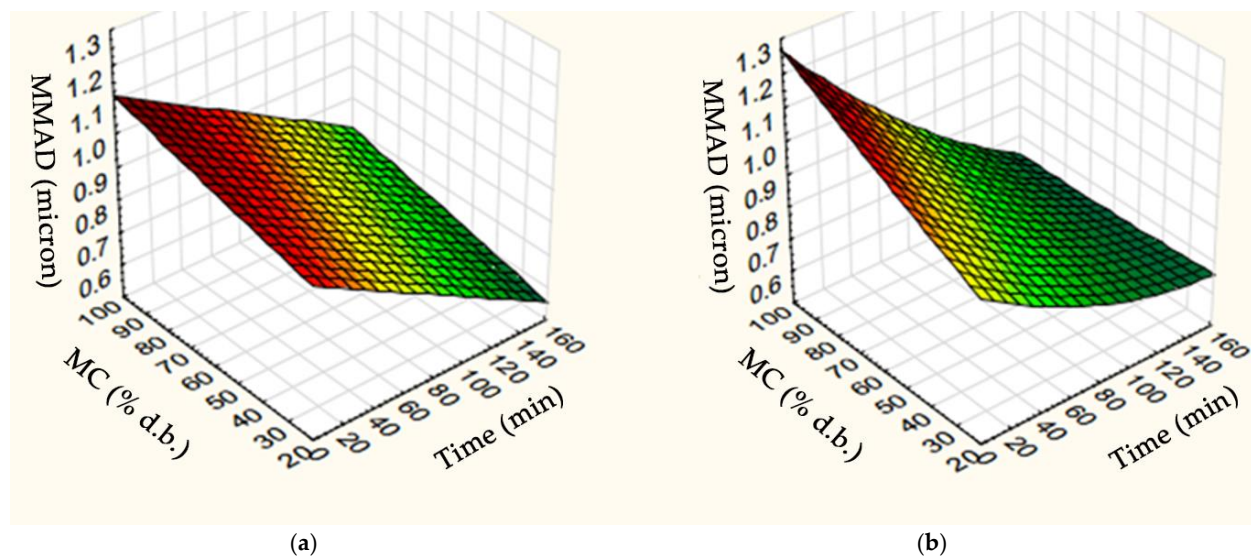


Figure 6. MMAD values' 3D surface plots by the first- and second-degree models: (a) First-degree model; (b) Second-degree model.

Table 2. Coefficient values of first- and second-degree models of MMAD prediction.

Degree in Model	Coefficient					
	P_0	P_1	P_2	P_3	P_4	P_5
First	0.9205	−0.0025	0.0019	−	−	−
Second	0.8661	−0.0027	0.0036	9.09×10^{-6}	-2.69×10^{-5}	4.12×10^{-6}

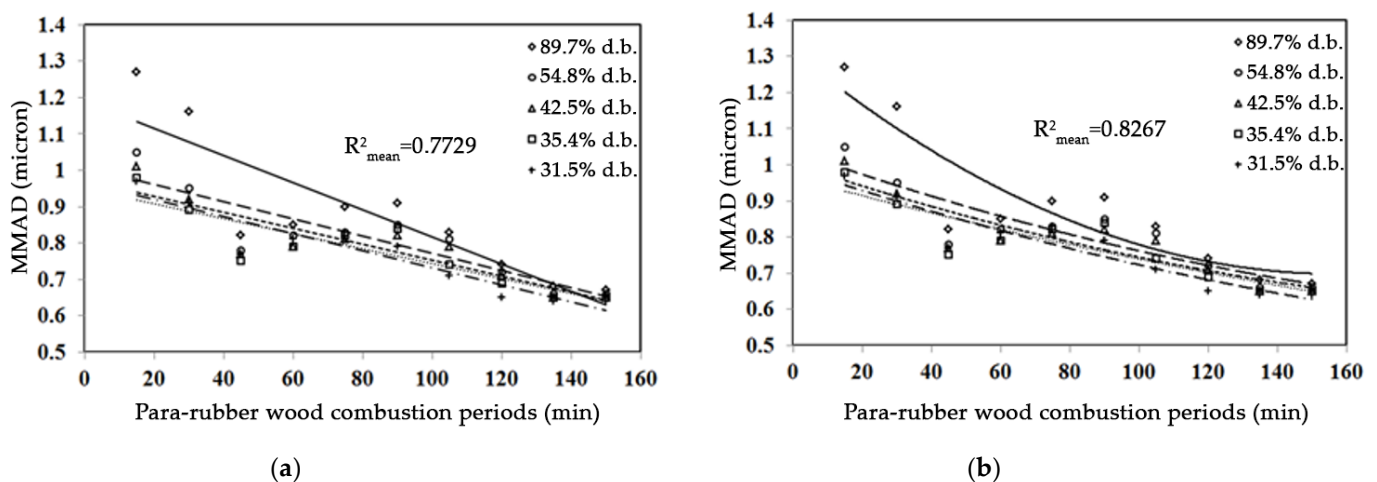


Figure 7. Comparison of predicted and experimental MMAD values: (a) First-degree model; (b) Second-degree model.

3.5. Prediction of TPMC Values Change

The TPMC values' 3D surface plots by the first- and second-degree models or Equations (3) and (4) are presented in Figure 8a,b. The x -axis and y -axis present the para rubber wood moisture content and burning time, respectively, while the z -axis shows TPMC values. These results showed that the moisture content of para rubber wood affected TPMC values when compared with the burning time. The p coefficient values in Table 3 were calculated by the least-squares method. As seen in Figure 8a,b, at the combustion period, the response of both models showed a decreasing trend of the TPMC values as the combustion time progressed, synonymous with the MMAD value. The response of the

second-degree model showed the effect of moisture content decreasing the *TPMC* value as the combustion time progressed.

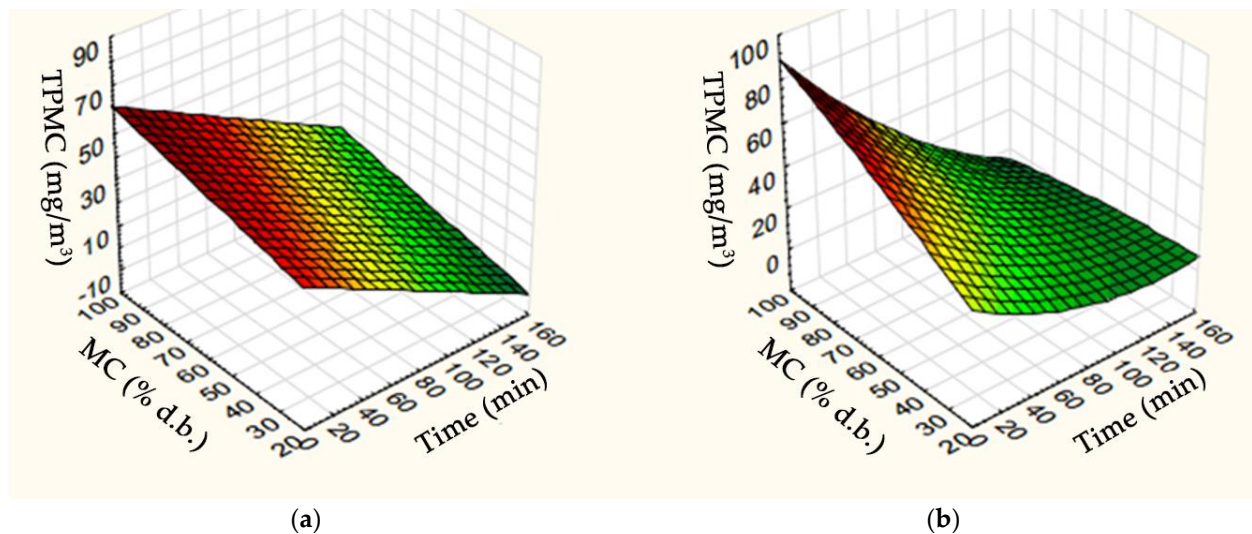


Figure 8. *TPMC* values' 3D surface plots by the first- and second-degree models: (a) First-degree model; (b) Second-degree model.

Table 3. Coefficient values of first- and second-degree models of *TPMC* prediction.

Model Degree	Coefficient					
	P_0	P_1	P_2	P_3	P_4	P_5
First	36.1114	−0.3261	0.2518	−	−	−
Second	18.6865	−0.3399	0.8332	0.0017	−0.0051	−0.0013

Comparing the *TPMC* data between the experimental results and prediction values, the second-degree model had a better fit in predicting than the first-degree model, similar to the *MMAD* data comparison; this result was confirmed by the higher mean of the coefficient of determination (Figure 9a,b), respectively.

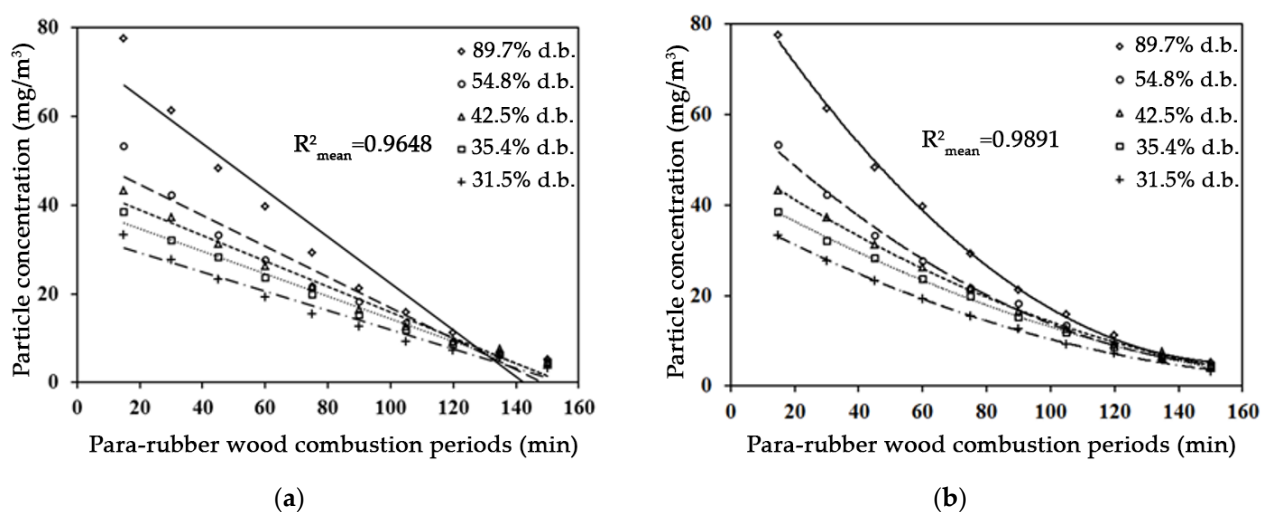


Figure 9. Comparison of predicted and experimental *TPMC* values: (a) First-degree model; (b) Second-degree model.

Besides wood moisture content and drying time, there may be other combustion rate variables that should be considered, such as air flow rate, pressure, atmosphere relative humidity, oxygen concentration in the atmosphere, and others. For example, water vapor, CO₂, N₂, and polyaromatic hydrocarbons (PAHs) are usually the result of a fuel-rich combustion at high temperatures (over 900 °C) [32–34]. Conversely, this is different from combustion at low temperatures (under 700 °C), resulting in CO, volatile organic compounds, smoke species, and soot coated in oxidized PAHs [32,35].

4. Conclusions

The results conclude that the smoke particle size distribution indicated a single-mode behavior. The highest *MMAD* and *TPMC* values were found in the initial combustion period with the highest moisture content for the para rubber wood. The moisture content and wood combustion period affected the change of temperature above the base of the fire. The *MMAD* and *TPMC* values increased with an increasing moisture content and a decreasing wood combustion period. In addition, between the first- and second-degree models of the *MMAD* and *TPMC* value prediction, it was found that the second-degree model was a better fit, with *R*² of 0.8267 and 0.9891, respectively. Future work for this modeling has been improved in the best prediction. The combustion rate, air flow rate, pressure, atmospheres relative humidity, and oxygen concentrations in atmospheres have been considered and analyzed.

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