Journal of Engineering Science and Technology
Vol. 14, No. 5 (2019) 2824 - 2835

PREDICTING THE EFFECT OF OPERATING PARAMETERS ON THE RADIAL TIRE TREADWEAR USING RESPONSE SURFACE METHOD

C. S. SUHAS KOWSHIK[1], NITHESH NAIK[2],
RITESH BHAT[3,*], NITHYANANTHAN PANNIR SILVAM[4]

[1,2,3]Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104 India
[4]School of Science and Engineering, Department of Mechanical Engineering, Manipal International University 71800 Nilai, Negeri Sembilan, Malaysia
*Corresponding Author: ritesh.bhat@manipal.edu

Abstract

Tire treadwear is a familiar problem found in tires. There are several factors that affect the treadwears in tires like tire geometry, operating conditions, tire materials, etc. The current work aims at investigating the effect of three operating condition variables viz., inflation pressure (30-36 psi), speed (20-60 kmph) and distance (100-300 km) on the response (treadwear). The study is based on tire specimen made of same brand and specification to eliminate the variations in the tire specific properties like material, geometry, etc. Central composite design form of response surface method is employed to create the experimental design, develop the regression model and optimize the variables. The speed is proved to be the highest influential variable on the response. The verification of the model shows that there is a high degree of correlation between the analytical and experimental results with a mean standard error of 3.245%.

Keywords: Central composite design, Optimization, Response surface method, Tire, Treadwear.

1. Introduction

Tire is a significant component of an automobile, which enables the interaction between the road surface and automobile. The principle function of the tire is to allow the steering control to travel from one point to other, in addition to providing load support. [1]. It exerts the necessary lateral forces to guide the vehicle with utmost safety during cornering and required longitudinal forces to transfer brake forces and engine power onto the road. Further, tires exhibit their appreciable damping properties by offering the essential adhesion and friction, during a variety of weather conditions. Tires, through suitable response characteristics, supports the steering inputs and exhibits reduced road noise and rolling resistance [2]. A tire, just like any other automotive vehicle component has certain sub-elements. The prominent ones are beads, an inner layer composed of a variety of fabrics, inner liner composed of compounded rubber, rubber-coated layers of materials (belt), carcass, sidewall, tread and the tread grooves. The various component of a simple tire is as represented in Fig. 1 [3].

Tires can be classified as radial and non-radial. The standard classification is based on the angle between the carcass cords and the tire plane. The adhesive properties of radial and non-radial tires differ and as represented in Fig. 2. The radial arrangements of the carcass allow the side-wall and tread to act independently [4].

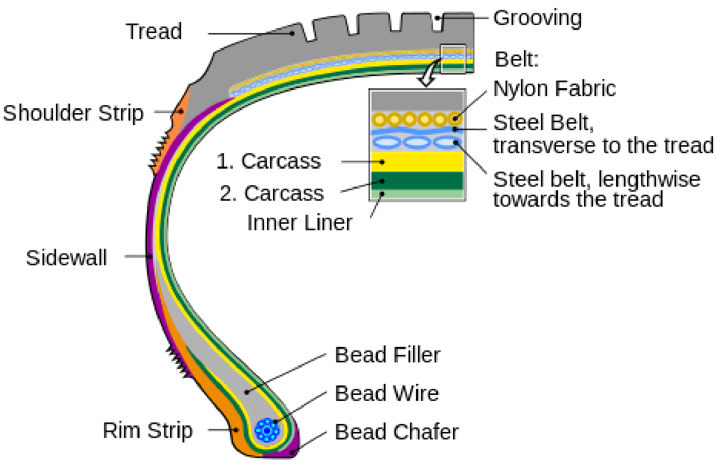


Fig. 1. Components of a tire.

(a) Radial. **(b) Non-radial.**

Fig. 2. Ground sticking behaviour of tires.

Sun et al. [5] conducted a life-cycle assessment of radial tires used in passenger vehicles and quantified the various impacts of each phase (manufacturing to end-of-life) on the environment.

The study emphasizes that there is a need to investigate the impact of various contributing factors towards the environment, particularly the tire wear. Tire wear (loss of outer rubber material) is the most common and unavoidable problem associated with tires caused due to the rolling and sliding contacts of the tire with road [6, 7]. Quicker the tire wear, quicker is its disposal. Larger disposal of used tires has a higher impact on the environment and hence needs to be addressed.

Veen [8] mentioned that tire wear could be classified into eight categories viz., lug wear, shoulder wear, centre wear, cupping, diagonal wear, one-sided wear, rib punch and spot wear. The process of wear continues to be a complex phenomenon as there exists no single definable wear rating inroad service to one tread compound. Since there exists, several factors that affect the tire wear, there is no one particular standard laboratory method of testing the tire wear [9]. Various researchers have clearly proved that the appropriate inflation pressure, alignment issues, vehicle overloading and worn out shocks contributes significantly to the tire wear [10]. Kienle et al. [11] and Steyn and Ilse [12] stated that the tire wear is equally affected by tire design, driving habit, road surfaces and climatic factors, in addition to rolling resistance, which in fact represents a function of vehicle speed.

This article focuses solely on treadwear of radial tires. Fujikawa et al. [13] examined analytically, the treadwear on tires caused during cornering. The distance, velocity and pressure were the constructs. Fluegge et al. [14] proved through their experimental work that inflation pressure has a strong influence on the tire tread wear in addition to tread design. The current work undertaken focuses on the tire samples from only one manufacturer and one type and hence the tread design factor is neglected. Researchers have mostly considered conditions like cornering, wheel alignment, etc. to evaluate the treadwear in tires. The occurrence of treadwear during normal driving conditions (flat roads with fewer turns) has not been addressed well. The paper hence focuses on investigating and predicting the effect of constructs (inflation pressure, speed and distance) on the response (treadwear) in the radial tires manufactured by one of the most popular brands for a flat road drive, employing experimental design.

Response surface method most commonly abbreviated as RSM is an assortment of analytical and statistical techniques. The statistical method is employed for generating models that deals with the relationship between the process variables and the response. The RSM models could either be designed using the Central Composite (CC) design or by Box-Behnken (BB) design. Based on studies by Yusri et al. [15], Mason et al. [16] and Philip et al. [17], the following may be summarized as the steps involved in RSM.

- Defining the input factors (continuous and categorical)
- Deciding the appropriate design for the experiment.
- Conduction of experiment and recording of the response data.
- Developing a mathematical model in the form of linear or quadratic equations.
- Statistical and mathematical analysis of the data.

RSM has been in usage since its development in the 50s has been consistently used in various research works. It has successfully proved to be one of the most effective statistical analysis tools, for predicting the effect of the process variables to minimize/maximize the response item

A second-order, a quadratic equation is used to model in most of the cases [18-23]. In general form, a second-order equation with just two input variables say, y_1 and y_2 and a response R is given in Eq. (1). a_1, a_2, a_3, a_4 and a_5 are the constant coefficients.

$$R = a_1 + a_2 y_1 + a_3 y_2 + a_3 y_1 y_2 + a_4 y_1^2 + a_5 y_2^2 \quad (1)$$

The Central Composite (CC) design of RSM is used in the current work, which marks to be the most popular form of the proposed method for predicting the effects of the constructs on the responses and generating the experimental design. CC design has proved its effectiveness in optimizing the constructs in various fields like manufacturing processes, medicines, biology and food science [24].

The following Section 2 of the article briefs about the materials and methods used in the current work. Section 3 deals with the results obtained and the comprehensive discussion regarding the findings. The article ends with a brief and crisp conclusion, in addition to the future scope (limitations) of the work in Section 4.

2. Materials and Methods

2.1. Design and fabrication of test-rig

A conceptual design of the test rig has been modelled using the CATIA V5 and the stress analysis of the same has been carried out using ANSYS 14.0. The final CATIA model of the test rig is as shown in Fig. 3.

After deriving the satisfactory results in the stress analysis stage, the required components were procured, and the test rig was fabricated. The fabricated test-rig used for the experiment has been shown in Fig. 4. The details of the procured items for the same is presented in Table 1.

Fig. 3. Conceptual model of test-rig using CATIA V5.

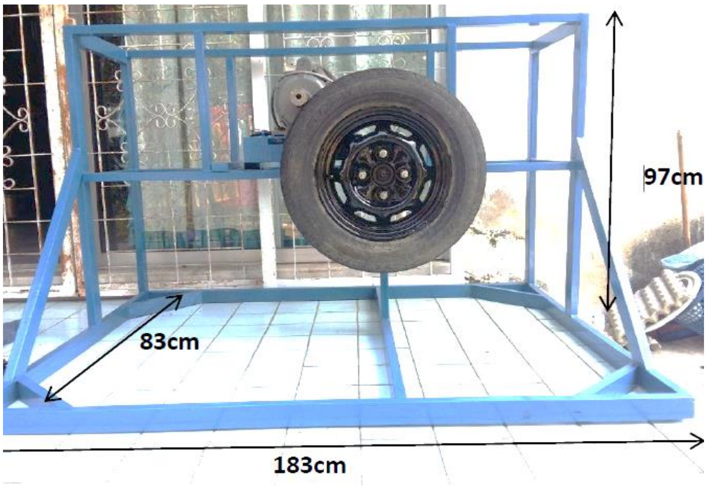


Fig. 4. Fabricated test-rig.

Table 1. Components used for fabricating the test rig.

Components/tools	Specification	Quantity
Rectangular carbon steel hollow rod	2-inch × 1 inch	20 m
	2-inch × 4 inch	1.5 m
Wheel hub and bearing	9 inch	1
Brand new radial tires*	175/70 H13	6
Steel wheel	13 inch	1
Bolt and nut	M12 × 2.5	8 each
Single-phase asynchronous motor with controller set	240 V, 6.1A, 800 W, 2800 rpm	1
Rough stainless steel rod	6-inch × 4 inch	1
Tire tread depth gauge	-	1
Digital tachometer	-	1
Spray paint	Solid blue and black colour	1 each

* Brand of tire shall not be disclosed in the entire work.

2.2. Experimental design

The central composite design in RSM is used to investigate the combined effect of the chosen constructs: inflation pressure, speed and distance travelled. Other variables: tire geometry, tire material and tire tread width are ignored as there exists no variation in the type and brand of tires used as a specimen. The range levels chosen for the experiment for each variable is shown in Table 2. The second-order model obtained from the CC design is further used to optimize the variables using a smaller number of experimental runs.

Table 2. Continuous factors with maximum and minimum levels defined for the experiment.

Independent variable (construct)	Code	-1	0	+1
Inflation pressure (psi)	Y_1	30	33	36
Speed (kmph)	Y_2	20	40	60
Distance travelled (km)	Y_3	100	200	300

Since the output speed of the asynchronous (induction) motor is in revolution per minute (rpm) and the required speed of tire is represented in kilometres per hour, Eq. (2) was used to convert the rpm to kmph, for the known wheel diameter of 13 inches.

$$Output\ motor\ speed\ (rpm) = \frac{Required\ tire\ speed\ (kmph)}{0.06} \quad (2)$$

The motor speed is then varied accordingly, using the speed controller set. The converted values of motor speeds for the selected speeds, calculated using Eq. (2) are given in Table 3. In this experimental work, MINITAB 18 is used for facilitating the application of RSM. ANOVA is used later, to investigate the significance of the process variables on the response.

The central composite experimental design comprising 20 trial runs for the undertaken work is given in Table 4.

Table 3. Continuous factors with maximum and minimum levels defined for the experiment.

Required speed (kmph)	Theoretically calculated value (rpm)	Motor speed selected (rpm)
20	333.33	335
40	666.66	670
60	1000	1000

Table 4. CC response experimental runs for treadwear.

Run	Inflation pressure (psi)	Speed (kmph)	Distance travelled (km)	Tire treadwear (mm)
1	36	40	200	0.010
2	33	40	200	0.030
3	33	20	200	0.040
4	33	40	200	0.060
5	33	40	200	0.060
6	30	60	300	0.143
7	30	20	300	0.050
8	30	60	100	0.040
9	33	40	200	0.090
10	36	20	300	0.030
11	30	40	200	0.052
12	33	40	200	0.075
13	36	60	100	0.125
14	33	60	200	0.135
15	33	40	300	0.200
16	33	40	200	0.120
17	36	20	100	0.091
18	36	60	300	0.250
19	30	20	100	0.034
20	33	40	200	0.110

3. Results and Discussion

3.1. Regression model fitting

The experimental runs and the corresponding response results (tire treadwear) have been presented in Table 2. The obtained data clearly shows that the tire treadwear increases with the increase in the values of chosen independent variables: inflation pressure, speed and distance travelled. The statistical analysis shows that the model fits significantly with the R^2 value of 83.51% and standard error of 3.44%. Further regression analysis and Analysis of Variance (ANOVA) is used for examining the statistical significance of the terms.

3.2. Results from experimental design

The response R is predicted for the radial tire treadwear of the selected brand used in most of the passenger vehicles in the selected geographical region. Equation 2 represents the reduced predicted model, expressed in terms of coded values as given in Table 5. Other terms have been neglected, as their coefficient is zero.

$$R = -6.71 + 0.431\,Y_1 - 0.0113\,Y_2 - 0.0028\,Y_3 - 0.007\,Y_1^2 \quad (2)$$

Table 5. ANOVA results for fitted CC response regression model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.06	0.01	5.63	**0.006**
Y_1	1	0.00	0.00	2.95	0.117
Y_2	1	0.02	0.02	16.98	**0.002**
Y_3	1	0.01	0.01	4.38	0.063
Y_1^2	1	0.01	0.01	6.97	**0.025**
Y_2^2	1	0.00	0.00	0.02	0.902
Y_3^2	1	0.01	0.01	8.90	**0.014**
Y_1*Y_2	1	0.00	0.00	2.54	0.142
Y_1*Y_3	1	0.00	0.00	0.32	0.584
Y_2*Y_3	1	0.01	0.01	7.88	**0.019**
Error	10	0.01	0.00		
Lack-of-fit	4	0.01	0.00	1.51	0.310
Pure error	6	0.01	0.00		

R^2 = 83.51%; Standard error (S) = 3.44%.

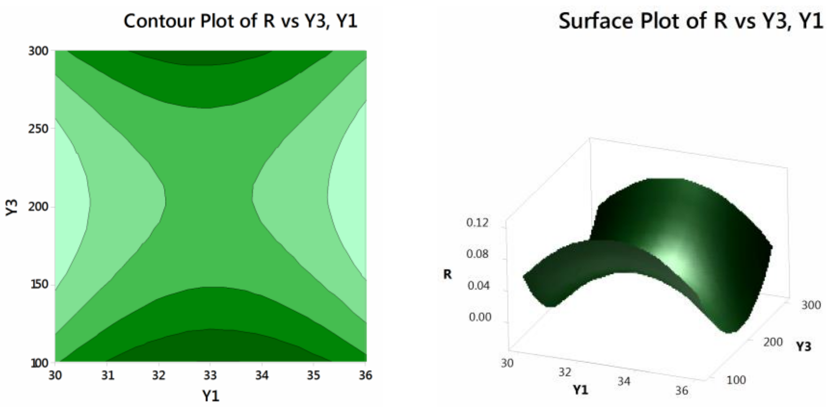
ANOVA results given in Table 5, show a significant model with just 3.44% of standard error. In addition, the results of this investigation also show that the model employed to adjust the response variable with a confidence level of 95%, adequate to depict the relationship between the response and the constructs. The ANOVA results also show that the predicted quadratic model holds significance with p-value <0.05.

In simple words, it proves the fact that the developed response regression model could be very well used to predict the treadwear of the tire on a normal road condition for the selected type and brand of tire.

From the ANOVA results in Table 5, it is also clear that speed is the most influencing variable. The other significant variable is squared terms of speed, the squared term of distance and interaction between speed and distance.

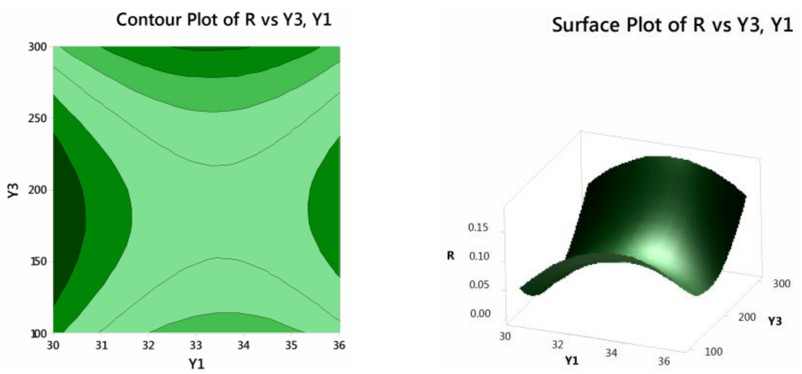
The influence of inflation pressure and distance at 20 kmph on the treadwear is shown in Figs. 5(a) and (b) through the contour and surface plots respectively. The mean treadwear at this speed is 0.060 mm. The changes in the obtained contour plot start from light green (0.00 mm) to dark green (0.12 mm), the dark green showcasing the peak value.

The influence of inflation pressure and distance at 40 kmph on the treadwear is shown in Figs. 6(a) and (b) through the contour and surface plots respectively. The mean treadwear at this speed is 0.105 mm. The changes in the obtained contour plot start from light green (0.03 mm) to dark green (0.18 mm), the dark green showcasing the peak value.



(a) Contour plot. **(b) Surface plot.**

Fig. 5. RSM plots for treadwear at speed = 20 kmph.

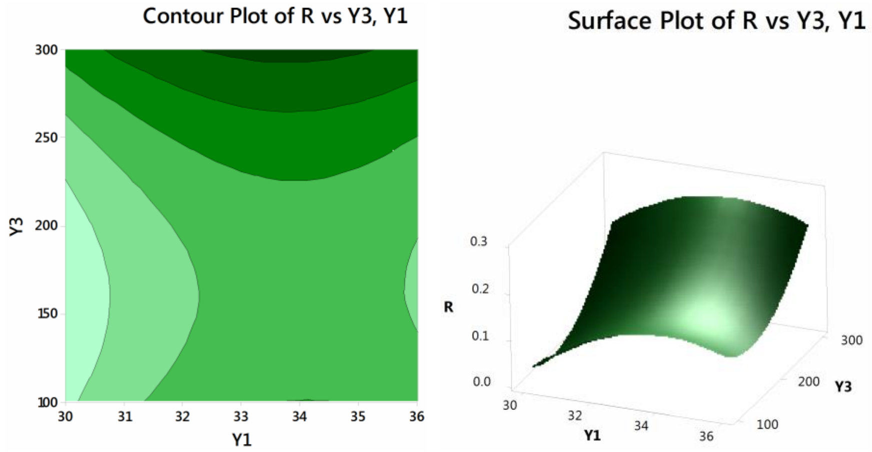


(a) Contour plot. **(b) Surface plot.**

Fig. 6. RSM plots for treadwear at speed = 40 kmph.

The influence of inflation pressure and distance at 60 kmph on the treadwear is shown in Figs. 7(a) and (b) through the contour and surface plots respectively.

The mean treadwear at this speed is 0.150 mm. The changes in the obtained contour plot start from light green (0.05 mm) to dark green (0.25 mm), the dark green showcasing the peak value.



(a) Contour plot. **(b) Surface plot.**

Fig. 7. RSM plots for treadwear at speed = 60 kmph.

3.3. Affirmation of RSM regression model

To validate the degree of appropriateness (94.33%) of the developed model as given in Eq. (2), the verification experiments are carried out with random levels of variables. The theoretically predicted maximum treadwear and the experimental treadwear values are shown in Table 6. The mean standard error is found to be 3.245%, which proves that there is a high degree of correlation between the experimental values and the theoretical prediction.

Table 6. Results of additional experiments for affirmation.

Y_1	Y_2	Y_3	Mean experimental result	Theoretical result	Standard Error %
30	50	100	0.048	0.045	3.125
36	45	200	0.054	0.058	3.45
32	40	300	0.163	0.174	3.16
			Mean standard error		3.245

4. Conclusions

The effects of speed, inflation pressure and distance travelled on tire treadwear of radial tires used in passenger cars is investigated. The tire specimens used are made of the same brand and are of the same specification. The experimental work comprised using response surface method for generating the model and statistically analysing it. Some concluding observations from the investigation are given below.

- Unlike other research on treadwear, wherein the inflation pressure was identified to be the most significant variable, the current work proves speed to be the most influential variable on the tire treadwear.

  The conditions considered for the assessment is the reason for the variation in the finding. The previous research mainly focused on the conditions like cornering and wheel alignment unlike the current study wherein, flat straight road condition was considered.

- The cornering of the vehicle occurs at lower speed and the wheel alignment does not accommodate the speed factor. In case of straight road runs (majorly on highways), the speed is high and gives rise to high frictional heat, causing high treadwear and the same has been proved using this experimental investigation.
- It is evident from Figs. 5 to 7 that irrespective of the inflation pressure and distance travelled, the treadwear increases with the increase in the speed. The reason for this might be due to high frictional heat caused due to high speed of the tire.
- There response regression model is well fit with standard error = 3.44% and R^2 = 83.51%. The quadratic model developed proves to be well suited for the experimental work having the p-value of model = 0.01 at 95% confidence level (α = 0.05).
- There is a high degree of correlation (94.33%) between experimental and analytical results, which is proved through the additional validating experiments (mean standard error = 3. 245%).

Yet another observation is that the contour and surface plot patterns representing the effect of constructs on the radial tire treadwear differ in case of 40kmph in comparison with the other two cases. The change in pattern may be further researched and considered to be one of the prime extensions to the current work.

Suspension alignment, tread geometry and several other factors in addition to speed, distance and inflation pressure, influence the tread wear. Nevertheless, these factors are not in the scope of the conducted work as the tire specimen used in the work are of the same brand and type. The effect of varying tire geometry and tire brand is also a possible extension to the current work.

Nomenclatures

a_1, a_2,.a_n	Constant values of coefficients
R	Response (tire tread wear)
Y_1	Speed in kmph
Y_2	Inflation pressure
Y_3	Distance travelled in kilometres
y_1 ,y_2	Input parameters

Abbreviations

ANOVA	Analysis of Variance
RSM	Response Surface Method

References

1. Thein, C.K.; Tan, H.M.; and Lim, C.H. (2016). Numerical modelling and experimental inflation validation of a bias two-wheel tire. *Journal of Engineering Science and Technology* (*JESTEC*), 4th EURECA 2015 Special Issue, 70-81.
2. Leister, G. (2018). *Passenger car tires and wheels (1st ed.).* Schwaigern, Germany: Springer International Publishing.

3. Jazar, R.N. (2008). Tire and rim fundamentals. *Vehicle dynamics: Theory and application*, 1-36.
4. Jazar, R.N. (2008). Vehicle dynamics: Theory and application. Boston, United States of America: Springer International Publishing.
5. Sun, X.; Liu, J.; Hong, J.; and Lu, B. (2016). Life cycle assessment of Chinese radial passenger vehicle tire. *The International Journal of Life Cycle Assessment*, 21(12), 1749-1758.
6. Da Silva, M.M.; Cunha, R.H.; and Neto, A.C. (2012). A simplified model for evaluating tire wear during conceptual design. *International Journal of Automotive Technology*, 13(6), 915-922.
7. Klüppel, M. (2014). *Wear and Abrasion of Tires*. Encyclopedia of polymeric nanomaterials. Berlin Heidelberg: Springer Verlag GmbH.
8. Veen, J. (2007). *An analytical approach to dynamic irregular tyre wear.* Master's Thesis. Mechanical Engineering Department. Eindhoven University of Technology, Eindhoven.
9. Grosch, K.A. (1992). Abrasion of rubber and its relation to tire wear. *Rubber Chemistry and Technology*, 65(1), 78-106.
10. Tong, G.; and Jin, X.X. (2013). Study on the simulation of radial tire vibration noise. *Applied Mechanics and Materials*, 273, 203-207.
11. Kienle, R.N.; Dizon, E.S.; Brett, T.J.; and Eckert, C.F. (1971). Tread wear and wet skid resistance of butadiene-styrene elastomers and blends. *Rubber Chemistry and Technology*, 44(4), 996-1014.
12. Steyn, W.J.v.; and Ilse, M. (2015). Evaluation of tire/surfacing/base contact stresses and texture depth. *International Journal of Transportation Science and Technology*, 4(1), 107-118.
13. Fujikawa, T.; Uchiyama, Y.; and Yamaguchi, I. (1999). Tire model to predict treadwear. *Tire Science and Technology*, 27(2), 106-125.
14. Fluegge, J.H.; Sparks, J.; and Vekselman, I. (1988). Tire treadwear experiment using Taguchi methods. *SAE Technical Paper 880580*, 11 pages.
15. Yusri, I.M.; Majeed, A.P.P.A.; Mamat, R.; Ghazali, M.F.; Awad, O.I.; and Azmi, W.H. (2018). A review on the application of response surface method and artificial neural network in engine performance and exhaust emissions characteristics in alternative fuel. *Renewable and Sustainable Energy Reviews*, 90, 665-686.
16. Mason, R.L.; Gunst, R.F.; and Hess, J.L. (2003). *Statistical design and analysis of experiments: With Applications to Engineering and Science* (2nd ed.) Hoboken, New Jersey, United States of America: John Wiley and Sons, Inc.
17. Philip, S.D.; Chandramohan, P.; and Rajesh, P.K. (2015). Prediction of surface roughness in end milling operation of duplex stainless steel using response surface methodology. *Journal of Engineering Science and Technology* (*JESTEC*), 10(3), 340-352.
18. Onwubolu, G.C.; and Kumar, S. (2006). Response surface methodology-based approach to CNC drilling operations. *Journal of Materials Processing Technology*, 171(1), 41-47.
19. Routara, B.C.; Bandyopadhyay, A.; and Sahoo, P. (2009). Roughness modelling and optimization in CNC end milling using response surface

method: effect of workpiece material variation. *The International Journal of Advanced Manufacturing Technology*, 40(11-12), 1166-1180.

20. Capella-Peiró, M.-E.; Bose, D.; Rubert, M.F.; and Esteve-Romero, J. (2006). Optimization of a capillary zone electrophoresis method by using a central composite factorial design for the determination of codeine and paracetamol in pharmaceuticals. *Journal of Chromatography B*, 839 (1-2), 95-101.
21. Ngan, C.L.; Basri, M.; Lye, F.F.; Masoumi, H.R.F.; Tripathy, M.; Karjiban, R.A.; and Abdul-Malek, E. (2014). Comparison of Box–Behnken and central composite designs in optimization of fullerene loaded palm-based nano-emulsions for cosmeceutical application. *Industrial Crops and Products*, 59, 309-317.
22. Nasirizadeh, N.; Dehghanizadeh, H.; Yazdanshenas, M.E.; Moghadam, M.R.; and Karimi, A. (2012). Optimization of wool dyeing with rutin as natural dye by central composite design method. *Industrial Crops and Products*, 40, 361-366.
23. Hao, J.; Wang, F.; Wang, X.; Zhang, D.; Bi, Y.; Gao, Y.; Zhao, X.; and Zhang, Q. (2012). Development and optimization of baicalin-loaded solid lipid nanoparticles prepared by coacervation method using central composite design. *European Journal of Pharmaceutical Sciences*, 47(2), 497-505.
24. Sukardi; Soeparman, S.; Argo, B.D.; and Irawan, Y.S. (2017). Optimization of patchouli oil (Pogostemon cablin, Benth) with steam distillation assisted by pulsed electric field via response surface methodology. *Journal of Engineering Science and Technology* (*JESTEC*), 12(8), 2106-2119.