ANN Analysis of Injection Timing on Performance Characteristics of Compression Ignition Engines Running on the Blends of Tropical Almond Based Biodiesel

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Abstract: In the present work, biodiesel prepared from Tropical almond oil (Terminalia Catappa) was used as fuel in C. I engine. Performance studies were conducted on a single cylinder four-stroke water-cooled compression ignition engine. Experiments were conducted for different percentage of blends of Tropical almond ester with diesel at different injection timings. Experimental investigations on the performance parameters from the engine were done. Artificial neural network (ANN) of back-propagation feed-forward Levenberg-Marquardt algorithm was used to predict the performance characteristics of the engine. An ANN model was developed for the performance parameters. To train the network, blend percentage, percentage load and injection timings were used as the input variables whereas engine performance parameters (brake thermal efficiency, exhaust gas temperature, and brake specific fuel consumption) were used as the output variables. The obtained experimental results were used to train the network structure. Results showed very good correlation between the ANN predicted values and the desired values for various engine performance values. Mean relative error values were less than 10 percent which by many standards is acceptable. The results show that ANN is an accurately reliable tool for the prediction of engine performance.

Keywords: Tropical Almond Ester, Injection Timing, Artificial Neural Network, Blend Percentage, Percentage Load, Brake Thermal Efficiency, Exhaust Temperature, Brake Specific Energy Consumption

1. Introduction

The agricultural sector in Nigeria is completely dependent on diesel for its power and to some extent for stationary applications. Increased farm mechanization in agriculture thus, has further increased the requirement of diesel. Nowadays due to the limited resources of fossil fuels, rising crude oil prices and the increasing concerns for the environmental security, there has been renewed focus on vegetable oils and animal fats as alternative fuel sources. The attractive features of the biodiesel are: (i) since it is a plant derived fuel, its combustion does not increase the current net atmospheric levels of CO_2, a greenhouse gas (ii) it can be locally produced, thus, providing opportunity for the possibility of reducing petroleum importation and (iii) it is

biodegradable, renewable and burns with clean gas. In most of the developed countries sunflower, peanut, palm and several other feed stocks are used as alternative sources. Therefore, in developing countries like Nigeria, it is desirable to produce biodiesel from oils which can be extensively grown throughout the country. It has been reported that almond oil is readily available in Nigeria. However, the major disadvantage of vegetable oils is their high viscosity which leads to poor atomization, which in turn may lead to poor combustion, ring sticking, injector coking, injector deposits, injector pump failure and lubricating oil dilution by crank case polymerization. [1-3] observed that converting vegetable oils into simple esters is an effective way to overcome all the problems associated with the vegetable oils. The conversion of vegetable oil into alkyl esters is

called transesterification. The transesterification process reduces the viscosity of the oil through the removal and replacement of glycerine with radicals of the alcohol [4]. Biodiesel fuels possess physicochemical properties that are similar to fossil based diesel [5] and can be used in compression ignition engine without modification; and it has been identified as a good alternative renewable fuel [6,7].Based on feedstock, there exist four groups of biofuels and they are: first, second, third, and fourth generation biofuels [8]. Generally, first and second generation biofuels are the most produced biofuels in recent times. First generation biofuels are derived from starch and sugar based crops (e.g. sugar cane, wheat, barley, rice etc.); while the second generation biofuels are derived from non-edible feed stocks such as agricultural residues (e.g. lemon peel, corn waste etc.), waste products (e.g. waste cooking oil), lignocellulosic plant biomasses, and plant oil containing seeds (croton megalacorpus tropical almond etc.). The third and fourth generation biofuels are obtained from microalgae biomass feedstock and genetically modified algae biomasses respectively. Problems associated with the commercialization of third and fourth generation biofuels are insufficient biomass production, low intensity of solar radiation partly due to season, and complexity and cost of harvesting microalgae [5, 8, 9-13]. Main problems attributed to the application of first and second generation biofuels include food crises and land availability since they are produced from crops [14-18]. Therefore, the use of tropical almond which is not a major food plant to produce biodiesel solves the issue of food-versus-fuel argument.

For a diesel engine, fuel injection timing is a major parameter that affects combustion and exhaust emissions. Proper ignition delay is necessary for ensuring proper pressure rise and peak pressure and hence maximum thermal efficiency, which in turn depends on the type of fuel also. [19] conducted experiments in a dual fuel CI (Compression ignition) engine to study the effect of injection timings on the exhaust emissions. They used ethanol blends with diesel and conducted experiments at five different injection timings. They observed that NOx and CO2 emissions increased and HC and CO emissions reduced for advanced injection timing. [20] carried out experiments on a single cylinder diesel engine with natural gas as the fuel. On advancing injection timing by 5.5˚ the engine showed erratic performance and when it was reduced to 3.5˚ he observed a smooth performance especially at low load conditions. Fuel consumption was slightly increased whereas CO and CO2 emissions were reduced. Similarly, second generation biofuels which tropical almond biodiesel belongs have been largely applied in operating internal combustion engines. The following works show how fuels derived from plant sources have been used to run CI engines. Ashok *et al*., [21] applied orange peel oil of 20% to evaluate performance and emission characteristics of a CRDi engine. The evaluation showed improved performance

with the use of biodiesel than conventional diesel fuel. The biodiesel produced higher brake thermal efficiency, mechanical efficiency and lower brake specific energy consumption under almost every operating conditions, especially injection timings. Ashok et al., [22] investigated the performance and emissions effects of 20% lemon peel oil operating a CRDI. Brake thermal efficiency, mean gas temperature and brake specific fuel consumption showed significant positive improvement at all operating conditions. The brake thermal efficiency improved by 33.3% more than that of diesel. Kumar et al., [23] investigated the performance and emissions profiles of lemon peel oil methyl ester blends on CI engine. The brake thermal efficiency showed higher improvement. The improvement was attributed to premixing and ignition delay. The brake specific fuel consumption was lower when biodiesel was used; and a necessary factor to associate it was high oxygen content of the biodiesel. Ashok et al., [24] made a comparative assessment of orange and lemon peel oil biofuels. The assessment shows both performance and emission parameters improved in significant amount. In all of that, the improved performance was basically associated to higher oxygen content, lower cetane number, and delayed ignition.

Manufacturers and engine application engineers usually intend finding out the performance of a C. I engine for various proportions of blends, for various compression ratios and at different injection timings. This requirement can be met either by conducting comprehensive tests or by modelling the engine operation. Testing the engine under all possible operating conditions and fuel cases are time consuming, costly and complex. On the other hand, developing an accurate model for the operation of a C.I engine fueled with blends of biodiesel is too difficult due to the complex nature of the processes involved. As an alternative, engine performance and exhaust emissions can be modelled by using artificial neural network (ANN). This modelling technique can be applied to estimate the desired output parameters when enough experimental data is provided. In the present work, experimental investigations of the performance and emissions of the diesel engine were conducted for different proportions of blends of tropical almond oil with diesel at different injection timing. subsequently, ANN models of multilayer perceptron (MLP) were developed and applied in predicting the performance characteristics using those experimental results. Among current estimation models used in performing data analysis, ANN possesses the best capabilities or qualities [23] and the multilayer perceptron (MLP) ANN structure is the most applied. Artificial neural network innovation was derived from the concept of human neurological system. It consists input layer neurons, hidden layer neurons, and output layer neurons, which are interconnect through a connecting weight [25-27]. Each of the layers contains neurons that are linked to the neurons of the next layers through weight interconnection. The input layer neurons without making

computation send input signals to the hidden layer neurons. All the hidden layer neurons make individual summation of all the inputs in such a way that once the combined summation is higher than activation value, the network produces an output. For any declared input, activation flow is transported from input layer to output layer via hidden layer [28]; and the process may be repeated as determined by error values. The errors are back-propagated into the neural network until it is sufficiently minimized. However, the error is the variation that exists between the predicted data and the experimental data. A well trained neural network has higher predictive ability [29]. Figure 1. shows how ANN is executed.
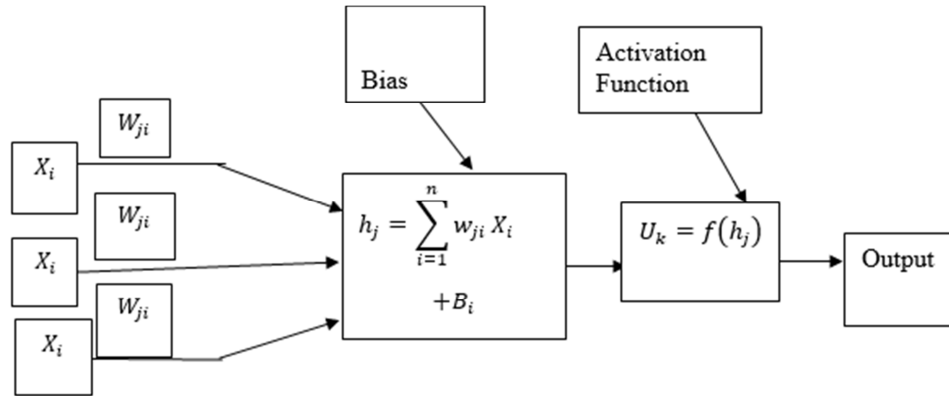

Figure 1. ANN computation process.

Where $U\kappa$ is the output,W_{ji} weights of the hidden layer,X_i are the values of the inputs,B_i is the bias of the hidden layer neurons. In the ANN execution, the inputs were blend percentages, brake load and injection timings, while the outputs were brake thermal efficiency, brake specific energy consumption and exhaust gas temperature.

Tropical Almond (Terminalia catappa) is a tall deciduous and erect tree reaching 15-25 m, trunk 1-1.5 m in diameter, often buttressed at the base. Its whorls are of nearly horizontal, slightly ascending branches spaced 1-2 m apart in tiers, or storeys, up the trunk. The pagoda-like habit becomes less noticeable as the branches elongate and droop at the tips. Its grey-brown bark becomes rough with age. Its fruit is hard to 7 cm, green-red, rounded and flattened, egg-shaped, with 2 ridges but no wings, 2.5 x 3-6 cm long, yellow or reddish when ripe. The cylindrical, oil-containing seeds are encased in a tough, fibrous husk within a fleshy pericarp. There are about 24 fresh fruits and 160 nuts per kg. It grows best in moist tropical climates. The tree is well adapted to sandy and rocky coasts and flourishes on oolitic limestone. Terminalia catappa. seed oil is of unsaturated type and contains mainly the fatty acids oleic C18:1(31.48%) and linoleic C18:2 (28.93%). The oil can be classified in the oleic-linoleic acid group. The oil extracts exhibit good physicochemical properties and could be useful for industrial applications.

It is often difficult to investigate the performance characteristics of a compression ignition engine using experimental means. This is because it is either always too time consuming to set up the rig, or very costly to purchase the components. Therefore, this study was aimed at investigating the effect of injection timing on performance parameters (BTE, BSEC and Texh) using Artificial Neural Network. The novelty of this study is that it is the first in literature to make extensive description of the application of ANN in investigation the performance of CI engines operated on tropical almond biodiesel.

2. Material and Method

2.1. Engine Test

The performance test was conducted in a single cylinder four stroke diesel engine. Figure 2. shows the diagram of the experimental setup used for conducting the experiments. It consists of a single cylinder four stroke water cooled compression ignition engine connected to an eddy current dynamometer. The compression ratio was 17.5:1. The specifications of the engine are shown in Table 1.

Experiments were conducted initially by using neat diesel at various loads and then using tropical almond oil blends. Experiments were repeated by changing injection timings. Matrix of the experiments conducted is as shown in Table 2.

Table 1 .Specifications of the Engine.

Engine	Four stroke, single cylinder, water cooled, constant speed diesel engine
Rated power	3.2 KW
Speed	1500 rpm
Bore	87.5 mm
Stroke	110 mm
Compression ratio	17.5:1
Crank angle sensor	Resolution 1°
Engine indicator	For data scanning & interfacing with Pentium III processor
Swept volume	661cc

Table 2.Experimental Conditions using tropical almond ester blends.

Operating parameter	Variations				
Engine Load (%)	0	25	50	75	100
Tropical almond ester blend (%)	20	40	60	80	100
Injection timing (°bTDC)	21	24	27		

Figure 2. Experimental Setup.

2.2. ANN Execution and the Performance Indicators

An ANN model for the biodiesel engine was developed by using the steady state experimental data. In the model 70% of the experimental data were used for the training set, while the

remaining 30% were employed for the test purpose. The inputs to the ANN were almond biodiesel blend percentage, load percentage, and the injection timing. The output parameters from the ANN were brake thermal efficiency (BTE), brake specific energy consumption, (BSEC) and exhaust gas temperature (T_{exh}).

The input patterns are presented to the network as a normalized array and are scaled in the range of 0.1 to 0.9. The original values are normalized for efficient processing by the network. The normalization is carried out using a linear mapping given by (1) as neural network was found to perform better in this range. [30,31].

$$\frac{A_L - A_{min}}{A_{max} - A_{min}} X(\text{High - Low}) + \text{Low} \qquad (1)$$

Where, A_i is the actual data, A_{min} is minimum data value, A_{max} is the maximum data value, high is the maximum normalized data which equals to 0.9, and low is the minimum normalized data which equals to 0.1. Figure 3 shows the mode of execution of ANN.
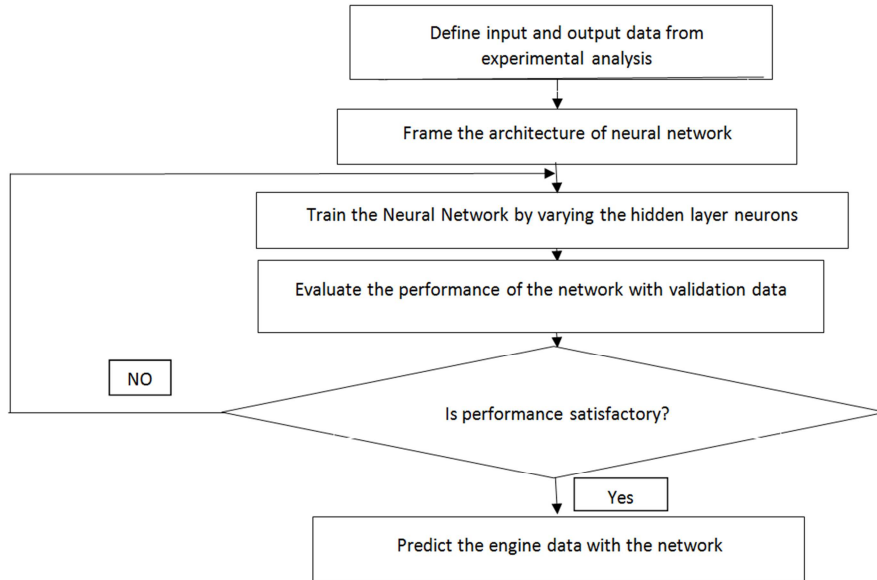

Figure 3. The stages involved in ANN model execution.

The network performance is measured through the correlation coefficient (R) and mean relative error values (MRE). The correlation coefficient is used to assess the strength of the relationship between the predicted and experimental values where R values closer to +1 indicate a stronger positive linear relationship, while R values closer to -1 indicate a stronger negative relationship. The mean relative error (MRE), which shows the mean ratio between the error and the experimental values, and R are shown in (2) and (3).

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{a_i - p_i}{a_i}\right| \times 100 \qquad (2)$$

$$R = \frac{\sum_{i=1}^{n}(a_i - \tilde{a}_i)(p_i - \tilde{p}_i)}{\sqrt{\sum_{i=1}^{n}(a_i - \tilde{a}_i)^2 \cdot \sum_{i=1}^{n}(p_i - \tilde{p}_i)^2}} \qquad (3)$$

Where n is the number of points in the data set, 'a' and 'p' are actual and predicted output sets respectively [32,33]. Finally, the root mean square error is obtained from (4).

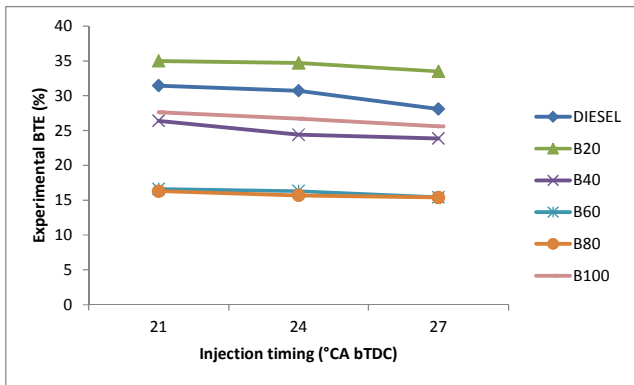$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(a_i - p_i)^2} \qquad (4)$$

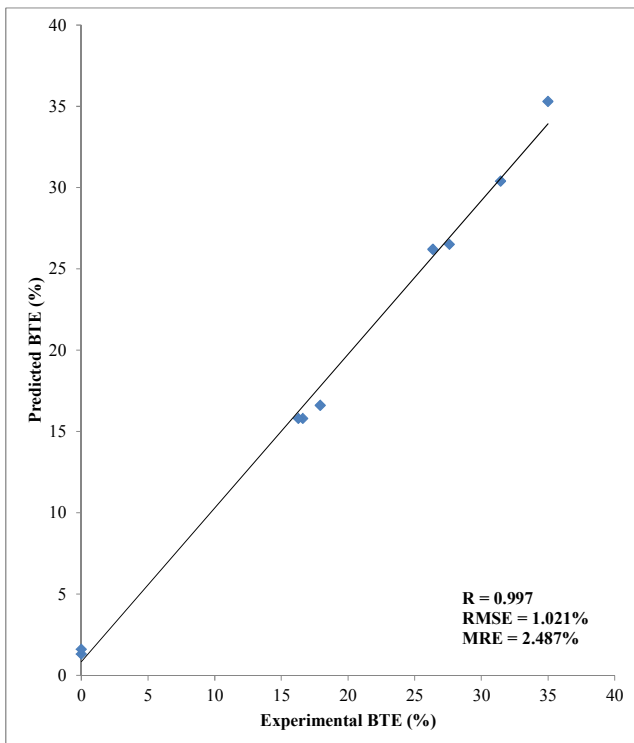## 3. Results and Discussion

3.1. Brake Thermal Efficiency (BTE)

(a) in Figure (4) indicates the variation of BTE with injection timings. Results indicated 20% blend of Tropical almond ester in diesel hasmaximum efficiency. Efficiency was found to be decreasing for higher blend proportions. This may be due to the decrease in the calorific value of the blend

for increased blend proportions. On advancing the injection timing there was an increase in the delay period which reduced the thermal efficiency. At retarded injection timing the delay period decreased which reduced the power because larger amount of fuel burns during expansion.
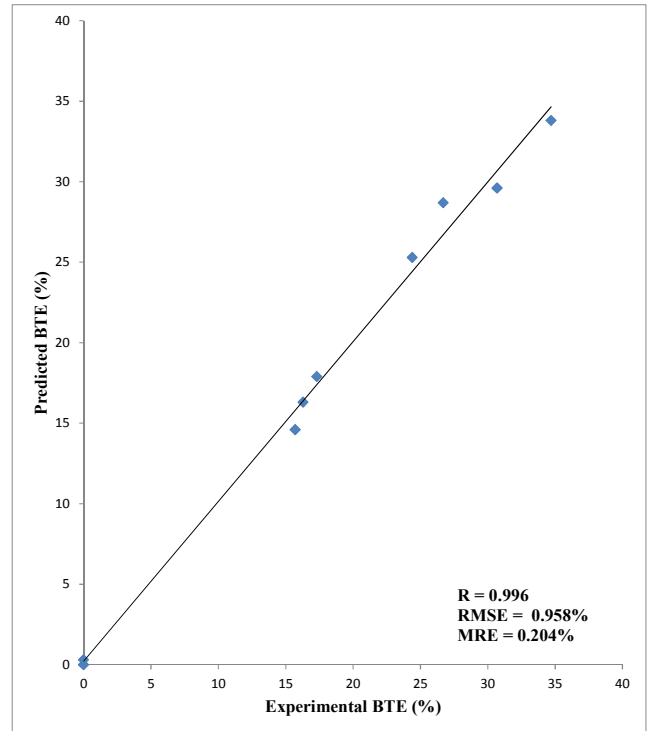
The ANN model for BTE 21°bTDC injection timing yielded a correlation coefficient (R) of 0.9976, mean relative error (MRE) of 2.48%, and root mean square error (RMSE) of 1.02% as shown in (b) in Figure (4). The predicted values of BTE as a function of experimental values at 24°bTDC injection timing are shown in (c) in Figure (4). A correlation coefficient (R) of 0.996, MRE of 0.24% and RMSE of 0.958% was generated by the ANN model. (d) in Figure (4) represents the values of BTE as a function of experimental values at 27°bTDC injection timing. A correlation coefficient (R) of 0.998, MRE of 3.39% and RMSE of 0.879% are shown by the ANN model.
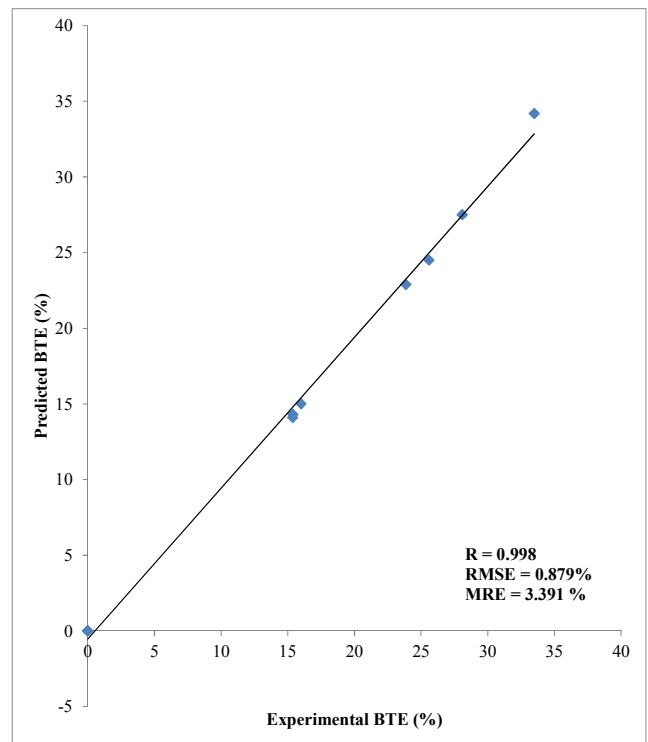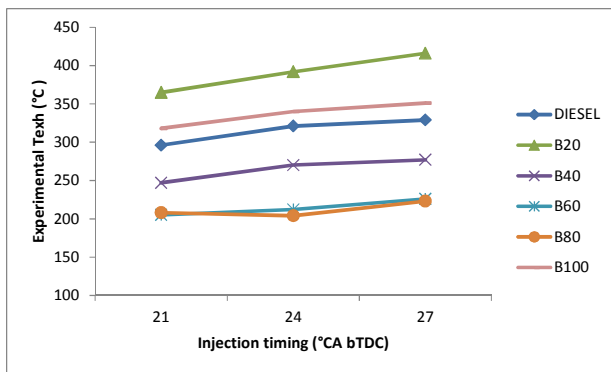

(a)

(c)

(b)

(d)

Figure 4. *ANN predicted against experimental values for BTE at different injection timings, $21^{o}BTDC$, $24^{o}BTDC$ and $27^{o}BTDC$.*
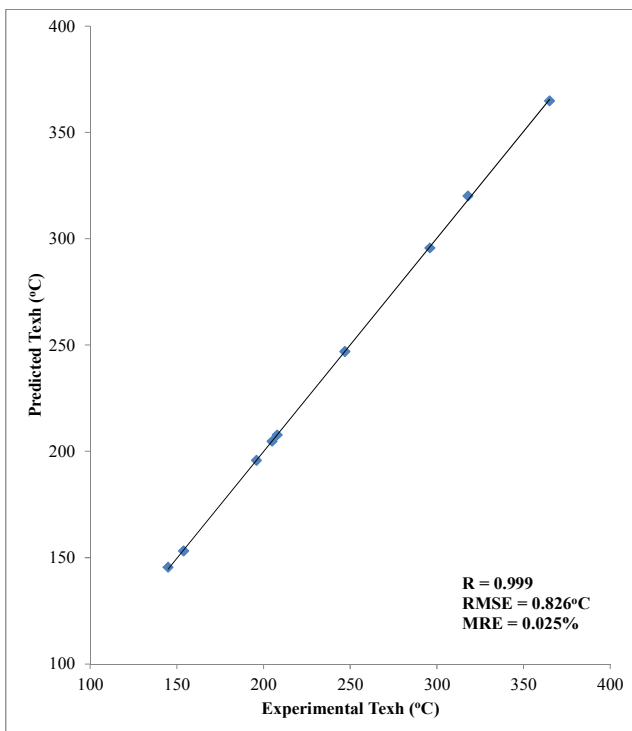
3.2. Exhaust Temperature (T_{ext})

(a) in Figure (5) shows the variation in exhaust gas temperature with injection timings. As the combustion is delayed, injected almond biodiesel fuel particles may not get

enough time to burn completely before TDC, hence some fuel mixtures tends to burn during the early part of expansion, consequently after burning occurs and hence increase in the exhaust temperature. With respect to the injection timings, advanced injection timing showed highest Texh. Retarding the injection timing has caused earlier start of combustion relative to TDC and hence complete combustion will take place and thus reducing the exhaust gas temperatures showing efficient combustion.
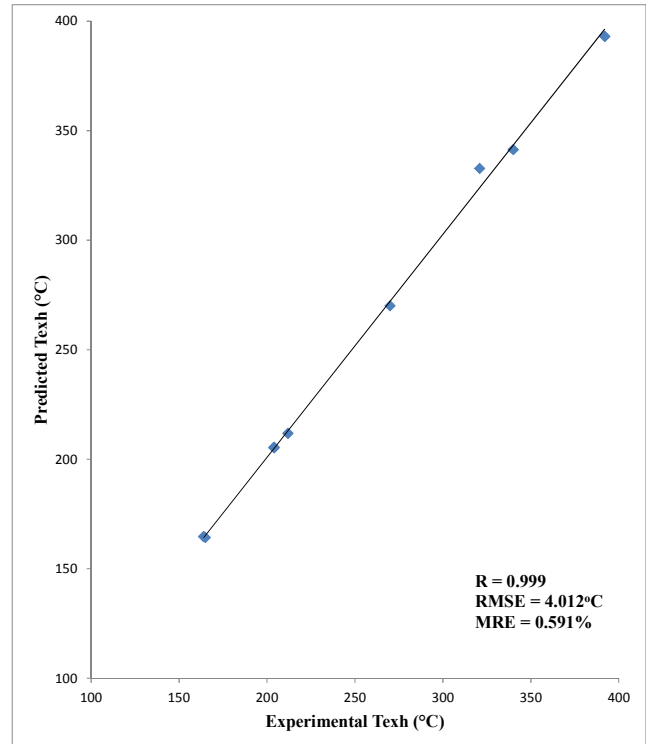
The ANN shows MRE of 0.025%, RMSE of 0.826°C and R of 0.999 at 21°bTDC injection timing as shown in (b) in Figure (5). The values predicted by ANN model and the experimental values for Texh at 24°bTDC injection timing are shown in (c) in Figure (5). The ANN model showed an MRE of 0.591%, RMSE of 4.012°C and R of 0.999. The ANN predicted values and experimental values for exhaust gas temperature at 27°bTDC injection timing are shown in (d) in Figure (5). The ANN model showed MRE of 0.448%, RMSE of 3.57°C and R of 0.992.
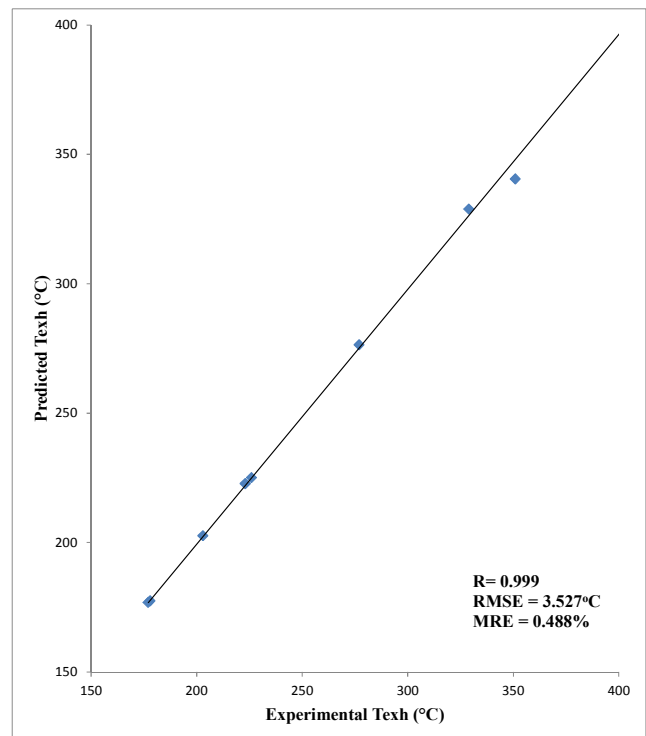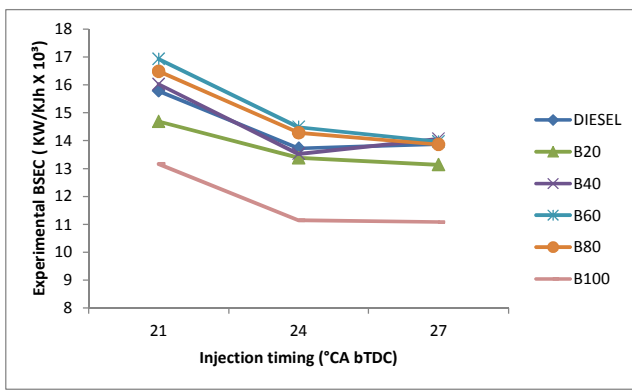

(a)

(c)

(b)

(d)

Figure 5. *ANN predicted against experimental values for T_{exh}. at different injection timings, 21°BTDC, 24°BTDC and 27°BTDC.*

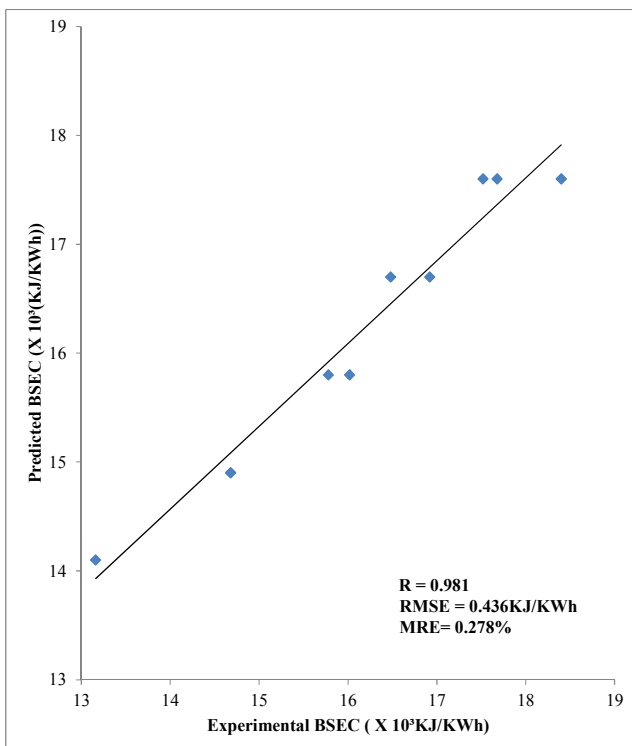### 3.3. Brake Specific Energy Consumption (BSEC)

(a) in Figure (6) shows the variation of BSEC for different injection timings. BSEC decreased with load for diesel as well as Tropical Almond ester blends. For 20% blend the

BSEC value was minimum compared with other blends, but higher than that for neat diesel. Advancing the injection by 3° reduced BSEC by 2.9%, and retarding the injection by 3° increased BSEC by 5.2%.
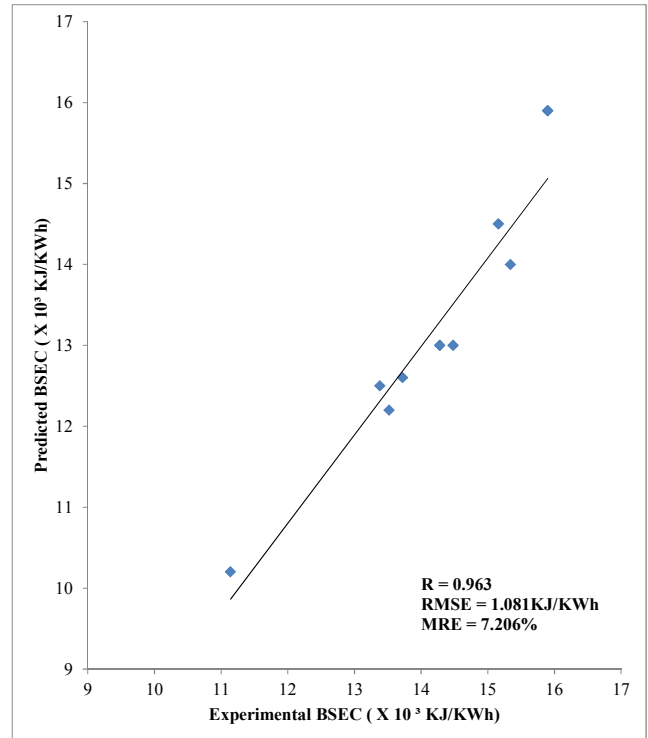
The ANN model prediction for BSEC at 21obTDC generated a correlation coefficient of 0.981 as shown in (b) in Figure (6). It was observed that the MRE value was 0.278% and the RMSE value was 0.436 KJ/KWh. (c) in Figure (6) revealed that the prediction of BSEC was in good agreement with actual values. A correlation coefficient of 0.963 was obtained for BSEC at 24obTDC. From (d) in Figure (6) the MRE value was 7.207% and the RMSE value was 1.081KJ/KWh. The ANN model prediction for BSEC at 27obTDC gave a correlation coefficient of 0.965. The MRE value was found to be 0.221% while the RMSE value was 0.978KJ/KWh.
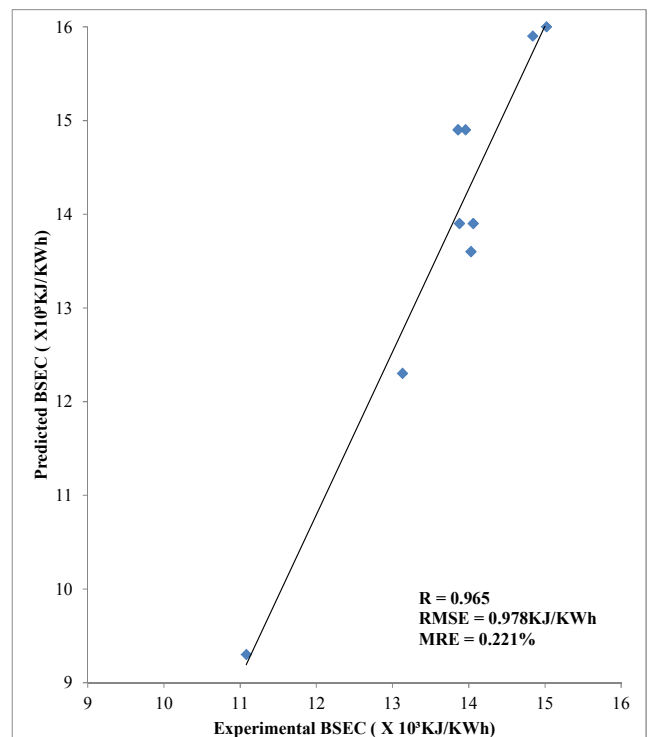

(a)

(c)

(b)

(d)

Figure 6. ANN predicted against experimental values for BSEC at different injection timings, $21^{o}BTDC$, $24^{o}BTDC$ and $27^{o}BTDC$.

4. Conclusion

After intensive assessment of the performance characteristics of compression ignition engine operated by

tropical almond ester blends using artificial neural network model of feed forward back propagation multilayer perceptron, the following core conclusions were reached:

Brake thermal efficiencies of biodiesel engine operated on Tropical Almond ester blends are very close to diesel and the 20% blend with diesel has shown maximum efficiency for biodiesel operation for all injection timings.

Brake specific energy consumption for biodiesel blends is more than that of diesel. With respect to the injection timings, retarding the injection timing from 24°bTDC increased the BSEC values.

Retarding the injection timing reduces the exhaust gas temperatures which shows efficient combustion.

ANN modeling was applied to predict the performance characteristics of a four stroke CI engine. It was observed that MRE of the test data for the performance and emission parameters were within 10%, which is acceptable.

The developed ANN model has been found to be useful for the prediction of engine performance parameters. This reduces the experimental efforts and hence can serve as an effective tool for predicting the performance of the engine and emission characteristics under various operating conditions with different biodiesel blends.

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