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Optimizing the Mechanical Performance of Green Composite Materials Using Muti-integrated Optimization Solvers

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ABSTRACT

Natural fiber composites are potential alternatives for synthetic materials due to environmental issues. The overall performance of the fiber composites depends on the reinforcement conditions. Thus, this work aimed to optimize the reinforcement conditions of the natural fiber composites to improve their mechanical performance via applying an integrated scheme of Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and differential evolution (DE) methods considering various reinforcement conditions including fiber length, fiber loading, and treatment time for optimal characteristics of the composite mechanical performance. The B-Spline approximation function was adopted to predict the experimental performance of green composites. The B-Spline approximation function demonstrated incomparable accuracy compared to linear or quadratic regressions. The function is then optimized using an integrated optimization method. Results have demonstrated that optimal reinforcement conditions for the maximized desired mechanical performance of the composite were achieved with high accuracy. The robustness of the proposed approach was approved using various surface plots of the considered input-output parameter relations. Pareto front or the non-dominated solutions of the desired output mechanical properties were also obtained to demonstrate the interaction between the desired properties to facilitate finding the optimal reinforcement conditions of the composite materials.

Keywords: B-Spline, composite materials, epoxy, mechanical properties, natural fibers, optimization

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INTRODUCTION

The undesirable impact of single-use plastics on the environment is currently an issue across the globe. The petroleum-based plastic packaging materials are continuously building up in landfills and leaching into the environment (AL-Oqla et al., 2021; Ariawan et al., 2022; Ismail et al., 2022; Wegmann et al., 2022). Handling plastic waste is important to the environment, and converting these wastes to biodegradable plastics can support reducing the environmental impact. The use of eco-friendly materials has been increasing with time as a result of global environmental awareness (Abral et al., 2019; Agarwal & Mthembu, 2022; Al-Jarrah & Al-Oqla, 2022; Al-Oqla et al., 2022; Vijay et al., 2021). Therefore, developing recyclable and environmentally sustainable materials has become an attractive and important field of research. Natural fibers have been utilized to replace petroleum-based synthetic fibers steadily.

The mechanical, thermal, electrical, and structural properties of natural fibers and biodegradable polymers are, somehow, different from synthetic fibers and petroleum-based plastics (Al-Oqla & Thakur, 2021; Al-Oqla & Hayajneh, 2022; Du et al., 2022; Fares et al., 2022; Ilyas et al., 2020). Composites are made of reinforcements set in a matrix. The reinforcement is usually the strong constituent used as the load-carrying material comparable to the matrix. Composites' acceptance has been boosted by their resistance to corrosion, low maintenance, ease of creating durable objects in one piece, and design flexibility. It has an influence on the maritime industry in developing strong items at lower costs (Al-Oqla et al., 2023; Al-Oqla & Sapuan, 2018, 2020; Aridi et al., 2016; Taraborrelli et al., 2019; Vijay et al., 2019).

Because of the beneficial properties, the abundance, and the low cost of natural fibers, they are considered a new generation of reinforcements for polymer matrices. The properties of the natural fibers are inconsistent based on several factors, including the age, type, climate, and place on the tree. Their mechanical performance is usually lower than other desired materials, but their specific properties are potential due to their relatively low density. Thus, arrangements with polymer matrices have been proposed (Al-Oqla, 2021b, 2023; Al-Oqla & Hayajneh, 2020; Balıkoğlu et al., 2020; Rojas et al., 2019). Natural-based composites are considered green bio-composites composed of natural fibers. The natural fibers added value to the bio-composites with a wide range of physical, mechanical, and biological properties. Production of bio-composites can be performed by various manufacturing techniques such as hand lay-up, compression molding extrusion, injection molding, sheet molding, resin transfer molding, filament winding, and pultrusion (Fairuz et al., 2014; Khan et al., 2018; Rababah et al., 2022). Several factors can affect the overall mechanical performance of green natural fiber composite materials, including the natural fiber type, the chemical treatment, the fiber/matrix compatibility, and the interface quality. The natural fiber's hydrophilicity and polymer matrix hydrophobicity affect the interfacial bonding between both materials in the bio-composites. To enhance such bonding, chemical and physical treatments are essential to the fiber surface (Al-Oqla, 2021a; Al-Oqla et al., 2022; Borsoi et al., 2020; Hayajneh et al., 2022; Nurazzi et al., 2021). Therefore, proper reinforcement conditions such as different fiber lengths, fiber types, and treatment conditions have to be optimized with various available methodologies, including optimization techniques, artificial intelligence, and others, in order to enhance the overall performance of composites (Al-Oqla, 2022; Al-Oqla & Al-Jarrah, 2021; BaniHani et al., 2022; Belaadi et al., 2020; Feito et al., 2019; Nawafleh & Al-Oqla, 2022a, 2022b).

Several studies were conducted to optimize the different parameters affecting the performance of natural fiber composites. Razak et al. (2012) were concerned with optimizing the PANI amount, the acid concentration, and the molar ratio in polyaniline-coated kenaf fiber composites. They aimed to obtain an optimal response for the unit break and the electrical conductivity characteristics (Razak et al., 2012). Another study by Toupe et al. (2015) was conducted to optimize four different mechanical parameters (tensile stress at yield, flexural modulus, tensile modulus, and impact strength) of flax fiber/postconsumer recycled plastic composite (Toupe et al., 2015). The input parameters considered were all extrusion-injection process parameters. Yusof et al. (2016) applied the Taguchi method to find the best fiber-matrix combinations and their weight ratio for optimal tensile strength (Yusof et al., 2016). Some other researchers used different methods for optimizing the natural fiber composites (Al-Shrida et al., 2023; Chaudhuri et al., 2013; Fares et al., 2019; Yaghoobi & Fereidoon, 2019).

Accordingly, this work aims to enhance the mechanical performance of green composite materials by optimizing the reinforcement environment of the natural fiber composites, considering various reinforcement conditions, including the fiber length, fiber loading, and treatment time, for optimal characteristics of the composite mechanical performance. It was performed utilizing B-Spline approximation functions to predict the experimental performance of the green composites and then optimizing these functions using an integrated solver of Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and differential evolution (DE) methods to end up with the optimal reinforcement condition for the maximized desired mechanical performance of the composite to enhance their implementations in various industrial applications.

METHODOLOGY

The approach developed here is composed of two stages. In the first stage, the experimental data are used to build prediction models for the tensile strength and the elongation to break percent in B-spline fitting functions. These B-spline functions' accuracy is statistically compared to the experimental values using the root mean square errors. Once the approximation functions are validated, the optimization is conducted in the second stage of this approach.

An integrated approach is developed to obtain the optimal conditions of fiber length, fiber percent, and treatment time for optimal characteristics for the tensile strength and the elongation percent of the composite to enhance achieving the optimal reinforcement conditions of the natural fiber-reinforced composite materials to maximize their desired mechanical performance. Here, a B-Spline approximation function is developed as a fitting function for the experimental data for each property (Tensile strength and elongation). To elaborate more, based on the desired orders in the input variables' domains, a B-Spline function based on the least squares approximation of the experimental data is established for both the tensile strength and elongation. Both B-Spline functions produce exact values similar to the experimental data with root-mean-square errors of less than $1x10^{-14}$.

Linear and quadratic regression functions are also derived as fitting functions for both properties to demonstrate the superiority of the B-Spline approximations over the regression approximations where large errors were found. The B-spline approximation functions are then optimized using an integrated solver composed of a Genetic Algorithm (GA), a Particle Swarm Optimization (PSO), and a differential evolution (DE). These solvers are operated simultaneously by sharing and interchanging the same population after each iteration. It will reduce the dependency of the solvers' accuracy on the tuning parameters involved and decrease the possibility of premature convergence to local solutions. The literature has more details on this optimization method (Rababah, 2011).

The optimization process covered all possible cases by optimizing the input conditions of fiber length, fiber percent, and treatment time for (1) maximizing the tensile strength, (2) maximizing the elongation percent, (3) minimizing the elongation percent, and (4) studying the combination of the tensile strength with the elongation percent where two cases are involved. Experimental data for the mechanical tensile properties of short and randomly oriented Borassus flabellifer fiber/ Epoxy composite materials with different fiber lengths, fiber loadings, alkali treatment times, and their corresponding tensile strength and elongation at break were adopted from literature (Balakrishna et al., 2013; Verma et al., 2015) and considered for the optimization. They are arranged and tabulated for convenience in Table 1.

Table 1
Mechanical properties of the fiber/epoxy composite for different fiber lengths, fiber percent, and heat treatment time

Fiber length (mm)	Percent of fiber	Alkali treatment time (h)	Tensile strength (MPa)	Elongation (%)
3	20	2	13.741	2.51
3	30	2	15.796	6.66
3	40	2	16.857	4.78

Table 1 *(Continue)*

Fiber length (mm)	Percent of fiber	Alkali treatment time (h)	Tensile strength (MPa)	Elongation (%)
3	20	4	14.866	10.47
3	30	4	16.451	3.57
3	40	4	17.187	6.09
3	20	6	17.416	2.42
3	30	6	18.178	5.32
3	40	6	19.742	4.27
5	20	2	20.612	4.06
5	30	2	19.165	12.17
5	40	2	20.499	15.89
5	20	4	20.853	5.35
5	30	4	19.980	3.27
5	40	4	21.158	6.42
5	20	6	20.585	9.56
5	30	6	21.602	13.79
5	40	6	22.296	8.6
7	20	2	19.116	2.5
7	30	2	21.604	4.65
7	40	2	21.899	1.84
7	20	4	21.733	17.37
7	30	4	22.471	19.40
7	40	4	23.174	11.45
7	20	6	22.766	3.70
7	30	6	23.008	3.24
7	40	6	27.283	10.23

RESULTS AND DISCUSSION

For comparison purposes, several regression models are developed and compared with the B-Spline approximation functions and the experimental data listed above.

Regression Approximation

The data provided in Table 1 are approximated to linear and quadratic regression functions for both properties (Tensile strength and elongation percent). The linear regression function is in the form:

$$R_1(x_1, x_2, x_3) = a_0 + a_1x_1 + a_2x_2 + a_3x_3 \tag{1}$$

where x_1, x_2, and x_3 are the fiber percent, the treatment time, and the fiber length, respectively. For tensile strength (TS), the linear regression function is expressed as:

$$TS_1(x_1, x_2, x_3) = 6.9767 + 0.10226x_1 + 0.65519x_2 + 1.4672x_3 \tag{2}$$

The comparison between the tensile strength obtained from the regression function with the experimental values is described in Figure 1 with a root-mean-square error of 0.9885 MPa.

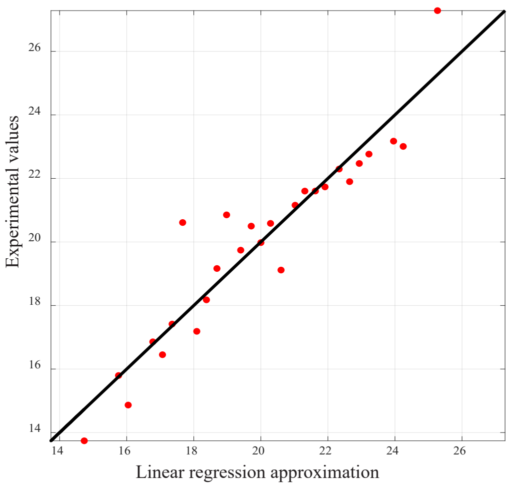


Figure 1. Linear regression vs. Experimental values of the tensile strength

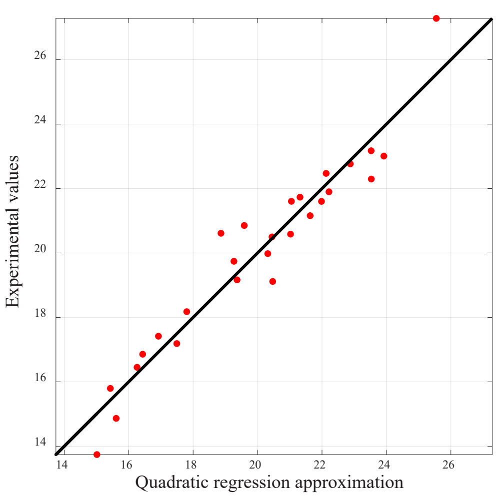


Figure 2. Quadratic regression vs. Experimental values of the tensile strength

Quadratic regression is also conducted for the tensile strength. The function is in the form:

$$R_2(x_1, x_2, x_3) = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_1x_2 + a_5x_1x_3 + a_6x_2x_3 + a_7x_1^2 + a_8x_2^2 + a_9x_3^2 \tag{3}$$

The regression function is expressed as

$$TS_2(x_1, x_2, x_3) = 6.9557 - 0.14001x_1 - 0.55986x_2 + 4.0275x_3 + 0.011533x_1x_2 - 0.004075x_1x_3 + 0.031167x_2x_3 + 0.0029294x_1^2 + 0.089153x_2^2 - 0.28072x_3^2 \tag{4}$$

The comparison between the tensile strength obtained from the quadratic regression function with the experimental values is described in Figure 2 with a root-mean-square error of 0.7849 MPa.

Their functions were represented as surfaces at constant values of the fiber length, as shown in Figures 3 and 4 for the linear and the quadratic approximations, respectively, to have better insight into the linear and the quadratic regression approximations and their accuracy compared to the experimental values.

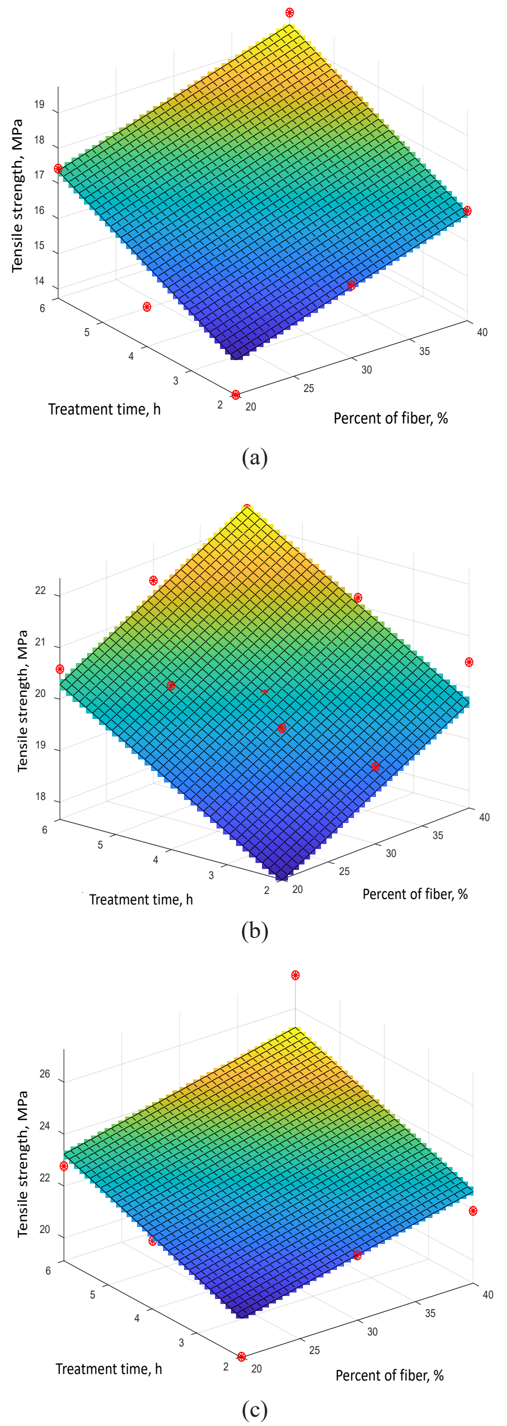


Figure 3. The linear regression approximation and the experimental data points for the tensile strength at fiber lengths of (a) 3 mm, (b) 5 mm, and (c) 7 mm

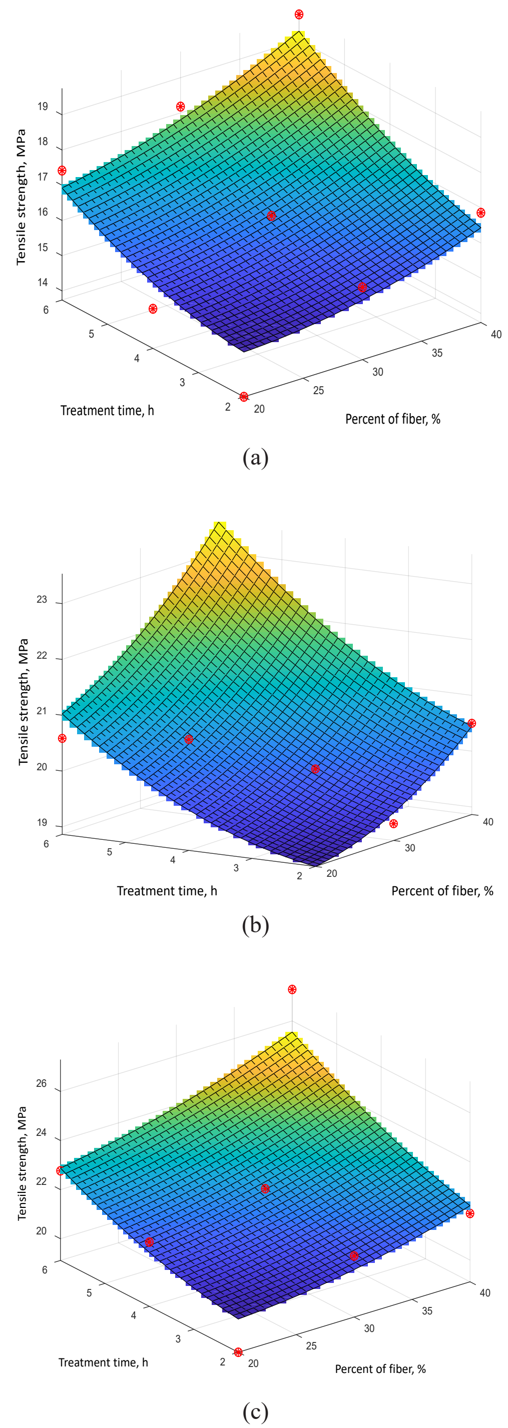


Figure 4. The quadratic regression approximation and the experimental data points for the tensile strength at fiber lengths of (a) 3 mm, (b) 5 mm, and (c) 7 mm

Similarly, the linear and the quadratic regression functions are generated for the elongation at break percent; the approximation functions revealed root mean square errors of 4.6287 and 4.2514 percent for the linear and the quadratic functions, respectively. Their values are plotted with the experimental values (Figures 5 and 6).

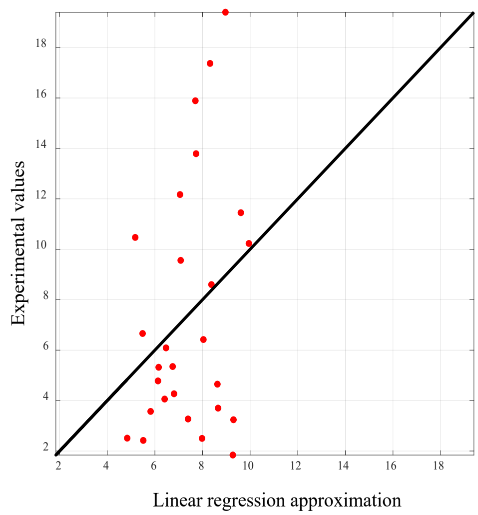


Figure 5. Linear regression vs. experimental values of the elongation percent

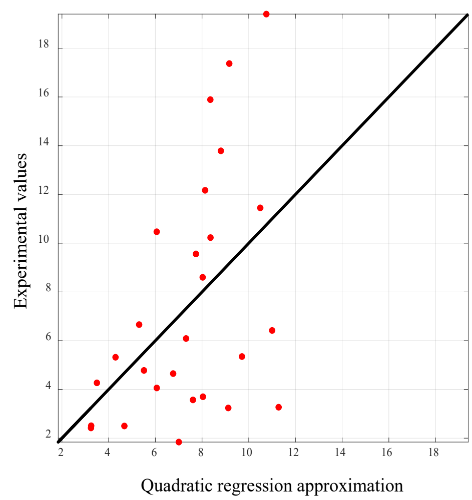
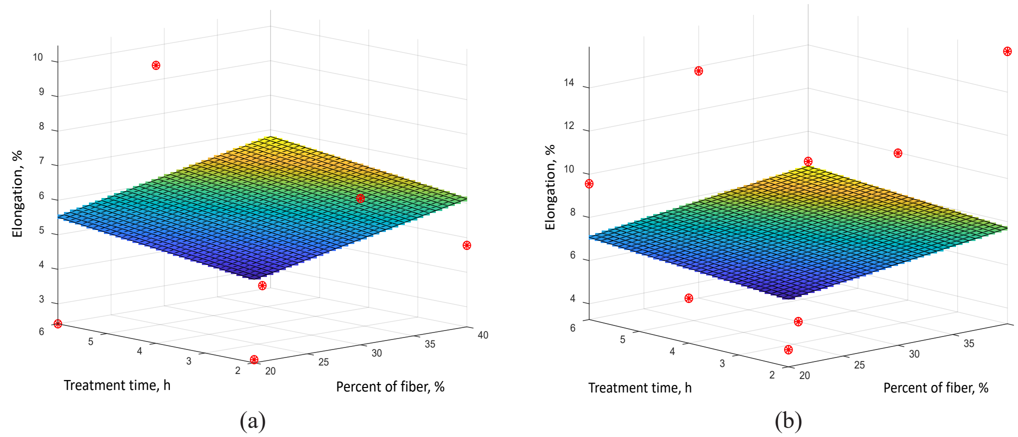
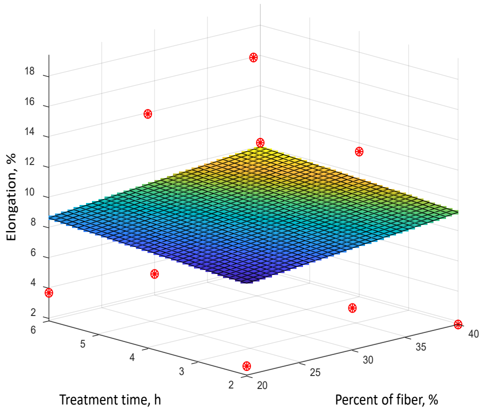


Figure 6. Quadratic regression vs. Experimental values of the elongation percent

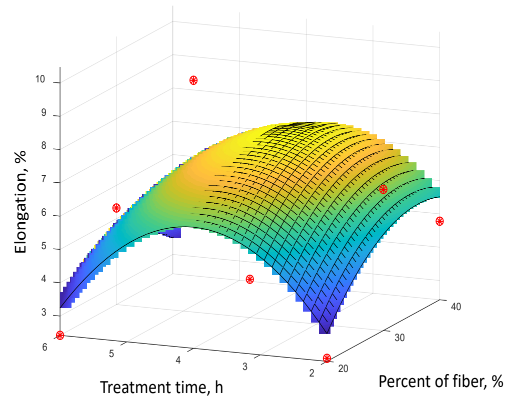
To better understand the regression approximations and their accuracy compared to the elongation percent's experimental values, their functions were also represented as surfaces at constant values of the fiber length (Figures 7 and 8) for the linear and the quadratic approximations, respectively.



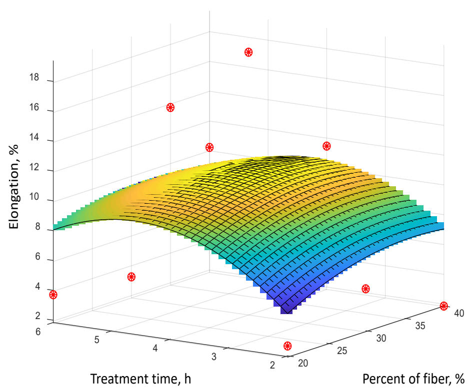


(c)

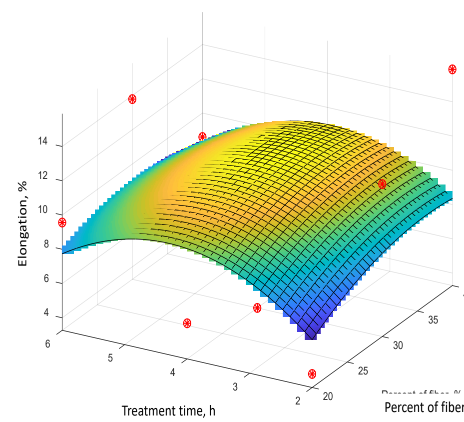
Figure 7. The linear regression approximation and the experimental data points for the elongation percent at fiber lengths of (a) 3 mm, (b) 5 mm, and (c) 7 mm



(a)



(b)



(c)

Figure 8. The quadratic regression approximation and the experimental data points for the elongation percent at fiber lengths of (a) 3 mm, (b) 5 mm, and (c) 7 mm

B-Spline Approximation

Considering the experimental data, two B-spline approximation functions are developed: $\mathbf{S_1}$ for the Tensile strength and $\mathbf{S_2}$ for the elongation percent. The B-Spline functions are in the form:

$$S(u,v,w)=\sum_{i=0}^{l}\sum_{j=0}^{m}\sum_{k=0}^{n}\mathbf{P}_{ijk}N_{i,r_1}(u)N_{j,r_2}(v)N_{k,r_3}(w) \qquad 0\le u,v,w\le 1 \tag{5}$$

where in general

$$N_{i,r}=(u-u_i)\frac{N_{i,r-1}(u)}{u_{i+r-1}-u_i}+(u_{i+r}-u)\frac{N_{i+1,r-1}(u)}{u_{i+r}-u_{i+1}} \tag{6}$$

where

$$N_{i,1} = \begin{cases} 1 & u_i \le u \le u_{i+1} \\ 0 & otherwise \end{cases} \tag{7}$$

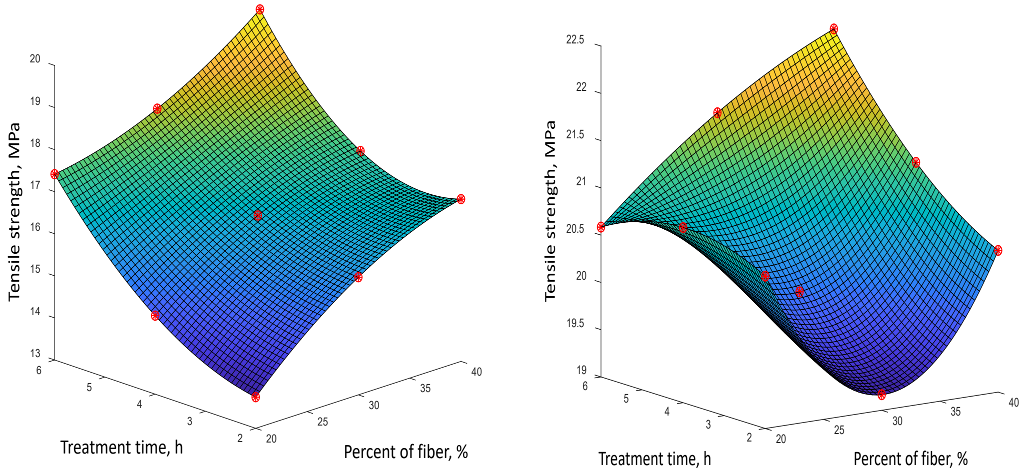
and the knot vector is defined as

$$\mathbf{KV} = u_i = \begin{cases} 0 & i < r \\ i - r + 1 & r \le i \le n \\ n - r + 2 & i > n \end{cases} \tag{8}$$

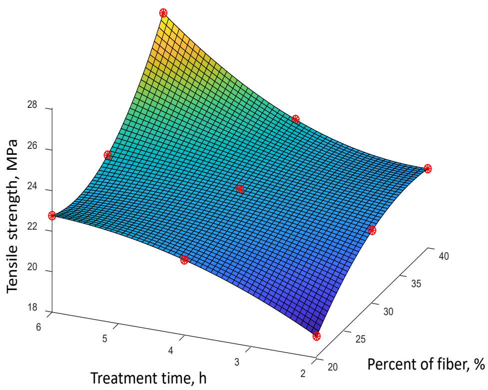
For the experimental data listed above, the B-Spline function is produced by considering $l = m = n = 2$, and the base function order $r_1 = r_2 = r_2 = 3$. $\mathbf{P}_{\mathrm{ijk}}$ are the control points of the B-Spline function that provide the best approximation for the data points.
A visual representation of the B-Spline approximation function is impossible since three input parameters affect the output. However, the B-Spline approximation function can be represented as a surface at a particular value of one input parameter (the fiber length). Figure 9 represents the B-Spline approximation function of the tensile strength as 3 surfaces at fiber lengths 3 mm, 5 mm, and 7 mm. The experimental data in Table 1 are also represented in the figure as 3D points to show the fitting function's accuracy and smoothness.

On the other hand, Figure 10 represents the B-Spline approximation function of the Elongation percent as 3 surfaces at fiber lengths 3 mm, 5 mm, and 7 mm. The experimental data are also represented in the figure to emphasize the smoothness and the accuracy of the fitting function.

However, before proceeding further with the optimization and to reduce the effect of the variances in both the inputs' spans and the outputs' spans on the accuracy of the B-spline functions or the sensitivity of the optimization method, the data provided in Table 1 is normalized and provided in Table 2 for convenience.

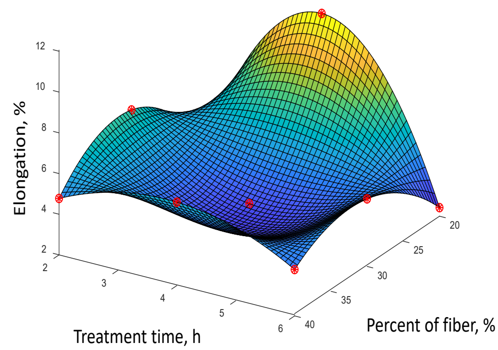


(a) (b)

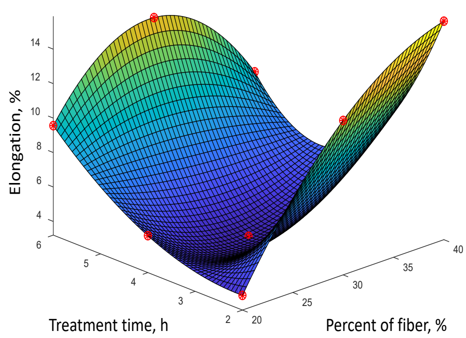


(c)

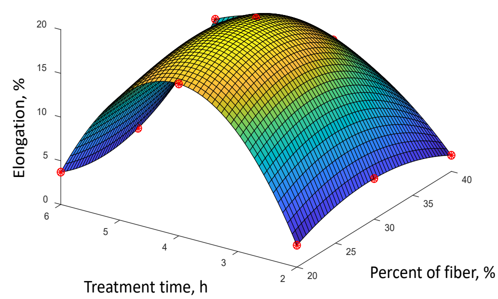
Figure 9. The B-Spline approximation and the experimental data points for the tensile strength at fiber lengths of (a) 3 mm, (b) 5 mm, and (c) 7 mm



(a)



(b)



(c)

Figure 10. The B-Spline approximation and the experimental data points for the elongation percent at fiber lengths of (a) 3 mm, (b) 5 mm, and (c) 7 mm

Table 2
Normalized values for the mechanical properties of the composite

Normalized values for fiber length	Normalized values for percent of fiber	Normalized values for treatment time	Normalized values for tensile strength	Normalized values for elongation percent
0	0	0	0	0.0382
0	0.5	0	0.1518	0.2745
0	1	0	0.2301	0.1674
0	0	0.5	0.0831	0.4915
0	0.5	0.5	0.2001	0.0985
0	1	0.5	0.2545	0.2420

Table 2 *(Continue)*

Normalized values for fiber length	Normalized values for percent of fiber	Normalized values for treatment time	Normalized values for tensile strength	Normalized values for elongation percent
0	0	1	0.2714	0.0330
0	0.5	1	0.3276	0.1982
0	1	1	0.4431	0.1384
0.5	0	0	0.5074	0.1264
0.5	0.5	0	0.4005	0.5883
0.5	1	0	0.4990	0.8001
0.5	0	0.5	0.5252	0.1999
0.5	0.5	0.5	0.4607	0.0814
0.5	1	0.5	0.5477	0.2608
0.5	0	1	0.5054	0.4396
0.5	0.5	1	0.5805	0.6805
0.5	1	1	0.6317	0.3850
1	0	0	0.3969	0.0376
1	0.5	0	0.5806	0.1600
1	1	0	0.6024	0
1	0	0.5	0.5902	0.8844
1	0.5	0.5	0.6447	1.0000
1	1	0.5	0.6966	0.5473
1	0	1	0.6664	0.1059
1	0.5	1	0.6843	0.0797
1	1	1	1.0000	0.4778

B-Spline Function Optimization

After showing the accuracy of the B-Spline approximation functions compared with the experimental data and normalizing these data, a global optimization method is required to predict the optimal conditions of the fiber length, fiber percent, and treatment time for optimal mechanical properties. An integrated global optimization method was utilized here (Churchwell et al., 2020; Sbayti et al., 2020). This method employs integration of the existing global optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) to run simultaneously by sharing and interchanging the same population at each iteration. It would increase the robustness of the optimization method by decreasing the possibility of premature convergence to some local solutions and by decreasing the dependency of the solvers' accuracy on the tuning parameters involved (Churchwell et al., 2020; Rababah, 2011).

The optimization is performed on the B-spline approximation functions developed to find the optimal conditions for optimal characteristics of (1) the tensile strength, (2) the elongation percent, and (3) the best combinations of both the tensile strength and the elongation percent. The lower and upper bounds of the inputs (fiber length, fiber percent, and treatment time) are set to 20% of the normalized values, that is [-0.2 1.2]. The optimization is provided as follows:

Tensile Strength Optimization. A population size of 500 is used. The optimization method required 4 main iterations with total function counts of 38173. The optimization method revealed that the best tensile strength could be obtained at the upper bounds for the fiber length, fiber percent, and treatment time at values of 7.8 mm, 44%, and 6.8 h, respectively. The tensile strength predicted at these conditions is 41.995 MPa.

This result indicates that the tensile strength increases with the fiber length, fiber percent, and treatment time. However, it is well known that this fact is not limitless. In other words, increasing these parameters above a specific threshold will reverse the process due to fiber agglomeration and decrease the fiber-matrix contacts. Thus, obtaining more experimental data beyond the upper bound will strengthen the accuracy of determining the optimal solution.

Elongation Percent Optimization. A population size of 500 is also used. The optimization method is conducted twice to obtain the optimal conditions for the global minimum and the global maximum of the elongation percent, as either can be important depending on the targeted application. The global maximum of the elongation percent is obtained after 4 main iterations with a total function count of 28328. The optimal conditions are a fiber length of 7.8 mm, a fiber percent of 26.77%, and a treatment time of 3.903 h. The maximum elongation is predicted as 31.507%. Conversely, minimizing the elongation percent is preferred for some applications. The minimization uses the same approximation function and reveals the best elongation characteristics near zero (0.0051%). It is obtained by setting the fiber length to 4.4314 mm, the treatment time to 2.0493 h, and the fiber percent to 16.1621%.

The optimal fiber length predicted is in the upper bound of 7.8 mm for maximizing the elongation to break percent. Care should be taken before generalizing this conclusion, as discussed previously.

Tensile Strength-elongation Percent Optimization. The tensile strength and elongation are important, with different weights depending on the applications. The combination of both characteristics is investigated, and the Pareto-fronts are generated. It is conducted by considering two cases for the optimal characteristics depending on the required applications: first, maximizing both the tensile strength and the elongation, and second, maximizing the tensile strength and minimizing the elongation percent.

For case I, where the goal is to maximize both the tensile strength and the elongation percent, a Pareto-front is obtained considering the optimal conditions of the fiber length, fiber percent, and treatment time in the range of the original data provided. In other words, the fiber length in the range [3 –7 mm], the fiber percent in the range [20 – 40%], and the treatment time in the range [2 – 6 h]. The Pareto front is shown in Figure 11. According to the Pareto-front, it is obvious that there is no dominant solution that can be adopted, and the selection will be dependent on the weight and importance of the two characteristics.

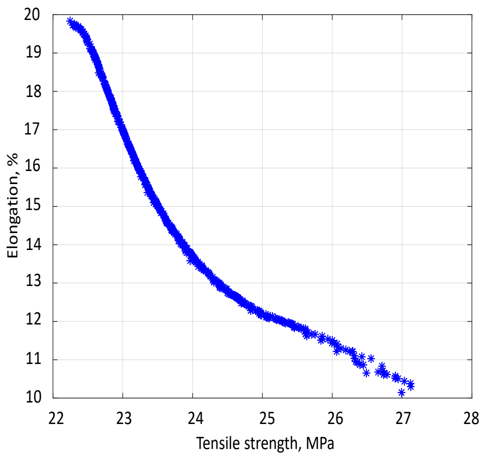


Figure 11. Pareto-Front for the optimal tensile strength and elongation percent, case I

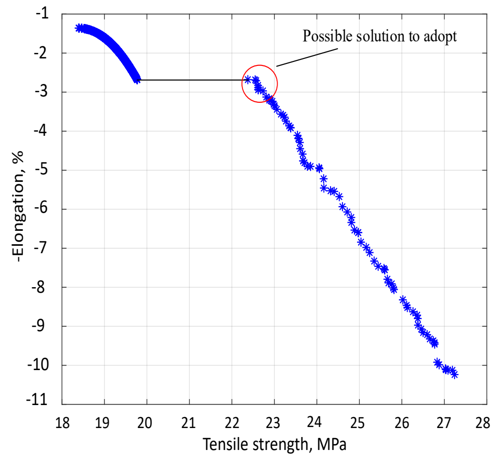


Figure 12. Pareto-Front for the optimal tensile strength and elongation percent, case II

For case II, the goal is to maximize the tensile strength and minimize the elongation percent. It is conducted and revealed in the Pareto front provided in Figure 12, where the elongation is multiplied by the negative sign for more convenience. A possible solution to be adopted is the region highlighted by the red circle with a tensile strength of 22.5481 MPa and an elongation percent of 2.6857%. This solution is obtained for a fiber length of 6.9992 mm, fiber percent of 27.3230%, and treatment time of 5.9974 h. However, as mentioned above, the final selection will completely depend on the weight and importance of the two characteristics according to the designer's and the consumers' needs.

Before proceeding to the conclusion, it is worth saying that the B-Spline functions can represent the scattered data than the regression models. Their fitting capabilities promote their use as prediction models. These models can be used for prediction or optimization purposes. However, to ensure accurate and robust results, it is recommended to work on wider ranges for the input parameters and to use larger experimental data.

On the other side, using the B-Spline functions in this way is restricted to parameters of numeric nature. In other words, finding the best fiber type, matrix type, or such categorized-nature parameters is impossible in the introduced approach.

CONCLUSION

Due to the characteristics of the natural fiber composites, where their overall performance depends on the reinforcement conditions, the optimization process for the reinforcement conditions is much desired. It can be concluded that the B-Spline approximation functions better represent the experimental data than the regression models. It was statistically measured in terms of the mean square errors. For tensile strength, the errors were $1x10^{-14}$ MPa, 0.9885 MPa, and 0.7849 MPa for the B-Spline approximation, the linear regression, and the quadratic regression, respectively. Moreover, for the elongation-to-break percent, the errors were 2.4×10^{-12}, 4.63, and 4.25 percent for the B-Spline approximation, the linear regression, and the quadratic regression, respectively. Optimizing the B-Spline functions was conducted using a multi-integrated optimization technique where all possible cases were investigated. The different combinations of the tensile strength and the elongation-to-break percent were also investigated. The optimization revealed that the optimal tensile strength of 41.995 MPa can be obtained for a fiber length of 7.8 mm, fiber percent of 44%, and treatment time of 6.8 h. The optimization also revealed that no dominant individual input solution is available to maximize overall performance. Thus, the non-dominated solutions of the desired output mechanical properties were obtained to demonstrate the interaction between the desired properties via Pareto-front figures that can be adopted for the desired combination depending on the weighted importance of the involved characteristics.

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