Water absorption of industrial high-density polyethylene biocomposites reinforced with Washingtonia filifera fibers: optimization using Fick's, RSM, and ANN models

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Abstract

The present study aims to investigate the phenomenon of water absorption scattering mechanisms and biocomposite kinetics by the immersion of different HDPE matrix reinforced with different amounts of *Washingtonia filifera* (WF) fibers (10, 20, and 30% by mass) in distilled water at room temperature. The response surface methodology (RSM) and artificial neural network (ANN) models were examined by considering WF fiber content and immersion time in the water absorption of HDPE/WF biocomposite. In this study, the central composite design (CCD) model of RSM was used to perform test design, modelling, and optimization. The process of water absorption was revealed to be tracking the diffusion mode of Fickian. The results obtained show that the addition of WF fibers to HDPE matrix reduced diffusivity. The results also reveal that ANN models were highly accurate in the prediction of water absorption with the training, validation, and test correlation coefficients of 0.9955, 0.9999, and 0.9915, respectively. The optimal conditions for maximum absorption were a fiber content of 29.88% and an immersion time of 752 hours. Moreover, a highly appropriate model to predict HDPE/WF biocomposites water absorption suitable for various industrial applications is proposed.

Introduction

The problem of water absorption is often related to a poor interface between matrix and fibers. Various studies have been conducted on the water immersion of natural fiber biocomposites in order to comprehend the water absorption process and determine the effect of moisture on the mechanical and chemical properties of these biocomposites [1–5]. Celino et al. [6] used Fick's law and Langmuir's model to describe the diffusive behaviour of four natural fibres (linen, sisal, jute, and hemp) that were exposed to two aging conditions (80% RH at 23°C). The results obtained show that the four studied fibers have a quasi-similar diffusive behavior. Another similar study, performed by Saidane et al. [7], estimated the experimental and analytical parameters (3D Fick model) of the moisture diffusion of linen/epoxy biocomposites at different quasi-unidirectional and twill configurations. A study was performed by Arbelaiz et al. [8] on the effect of short flax fiber content on the diffusion kinetics of flax-polypropylene composites aged by total immersion in water at 23°C. The authors observed a proportionality between the diffusion parameters and the fiber content of the composites. Recently Elsadig et al. [9] experimentally investigated the effect of water absorption on the mechanical behavior of date palm khalsa fibers (KDPLF) and epoxy-based composites that were reinforced with KDPLF. They found that, as the percentage of hemicelluloses increases in these fibers, the water absorption capacity of the fibers increases. On the other hand, for the biocomposite, they noticed that the water absorption decreases due to the filling of the lumen by the epoxy resin. A recent study by Ighalo et al. [10] involved modeling the water absorption behavior of plantain skin and bamboo fiber reinforced polystyrene composites using ANN modelling. The results showed low RMSE values (< 1 wt%), revealing that in actual use of the model, a high accuracy threshold would be expected for ANN predictions of water absorption of the composites. On the other hand, Le Duigou et al. [11] evaluated the effect of water aging of biocomposites reinforced with flax fibers immersed in distilled water for two months. The results obtained showed that the unidirectional flax fiber reinforcement is responsible for a rapid and relatively high water absorption in the biocomposite and the stiffness of the fibers is reduced by 40% after 2 months of immersion in water. Djellouli et al. [12] studied the transient hygroscopic behavior of a flax fiber-reinforced epoxy unidirectional (UD) composite aged by immersion in tap water at room temperature until saturation. They found that the diffusion coefficient (D_x) found is 100 times larger than D_z and about 2.3 times larger than D_y. This difference is related to the composition of the flax fiber which favors the transport of water in its stem especially through the lumen. Scida et al. [13] studied the effect of hygrothermal aging on the mechanical properties of epoxy biocomposite based on unidirectional flax fibers for two months under RH = 90% climate conditions at 20°C and 40°C. The authors found that the Young's modulus and the tensile strength were decreased by 60% and 14%, respectively. This decrease was due to the reorientation of the flax fiber microfibrils and the plasticizing effect of water on the matrix. An experimental study on the durability of carbon/linen fiber reinforced polypropylene and flax fiber biocomposites was conducted by Cheng et al. [14]. The samples were exposed to aging by immersion in water at elevated temperature until saturation (at 60°C for 300 hours). The authors found that carbon fibers reduce water absorption in the polypropylene/linen biocomposites and improve their mechanical properties (tensile properties and flexural properties). Melo et al. [15] investigated the non-Bickian water absorption process in a plant fiber-reinforced polymer composite using the Langmuir-type model, evaluating the influence of mass diffusivity on the process. They observed that mass diffusivity effectively influences water absorption behavior, especially at the beginning of the process, where higher differences in water migration rates in the material are found. There are many researchers who have used RSM and other methodologies to develop and model their experimental data [16–20]. Owolabi et al. patterned and optimized the relevant variables for the styrene solution polymerization by means of the response surface methodology [21].

The objective of this present study was to evaluate and validate the analytical model, developed from Fick's law of diffusion, in order to elucidate the implications of the immersion time. Then, to explore the effect of fiber reinforcement and their water immersion time. RSM and ANN methods were adopted to model the absorption of the newly developed HDPE/WF biocomposite and to critically compare the predictive capabilities of the two models. Surface response methodology using CCD was applied to develop the experimental design and to generate a representative model equation that allowed the water absorption based on these process factors.

Materials And Methods

2.1. Preparation of fibers and biocomposites

In this study, WF fibers were used. This fiber is easily grown locally in the region of Skikda (Algeria). WF fibers are extracted manually and then immersed in distilled water to wash off surface impurities. To remove moisture, the fibers are dried under natural conditions (at room temperature, 20°C for 10 days) before the fabrication of the biocomposite. The polymer used as a matrix is polyethylene (HDPE) reference PPC10642. It was supplied by SABIC Petrochemicals (HDPE blow molding, 95% purity and above, an average MFI of 0.4 and an average density of 0.96).

The biocomposite is manufactured on two Thermotron-C.W. Brabender type rollers (Model T303). First, 20% by mass HDPE is melted on the rollers at 170° C [22]. The WF fibers are cut (between 5 and 10 mm) and the rest of the HDPE is added and mixed for 7 min at 60 rpm. Then, the biocomposite is mixed 5 to 6 times for 5 minutes to improve the homogeneity of the material. After this, the processed biocomposite is removed from the rollers and cut to fit the mold size. The samples are prepared in a mold that is held at 190 ± 3°C using a Dake brand press for 20 minutes under a pressure of 20 MPa. Finally, the mold is cooled to 60°C using cold water. Table 1 shows the mass compositions of the different formulations produced.

Table 1
Mass composition of the different formulations elaborated in this work.

Designation	Biocomposites
HDPE/10%WF	High density polyethylene HDPE with10% of WF by weight
HDPE /20%WF	High density polyethylene HDPE with 20% of WF by weight
HDPE /30%WF	High density polyethylene HDPE with 30% of WF by weight

2.2. Water absorption

The study of the effect of WF fiber content on the diffusion kinetics of HDPE/WF biocomposites by total immersion in distilled water at room temperature consists of following the mass evolution of the samples over time, measured at regular intervals over a total period of 21 days (500h). At the time of the measurement of the mass, the samples were taken out of the bath and lightly wiped with an absorbent paper to eliminate the film of water present on the surface. Weighing was done on an electronic balance (accuracy of measurement = 0.0001 g). Water absorption tests were performed according to the ASTM standard method [23]. During aging, the mass gain of a biocomposite sample at time t expressed as a percentage, *Mt* (%), was determined according to Eq. 1.

$$Mt(\%) = \frac{(mt - mo)}{mo} \times 100$$

1

with m_t: weight of the composite at the time t, m_0: initial mass of the dried sample.

2.3. Fick’s model

Mathematical modeling of the water diffusion process in biocomposites is very important to control the diffusion mechanism. The numerous diffusion phenomena present in nature are described by Fick’s laws and can be characterized by their diffusion coefficient D. We have the first Fick’s law given by the following equation:

$$\phi = -DgradC$$

2

where D: diffusion coefficient of the medium inmm^2/s;

C: concentration of the solvent in the medium

Considering a thin plate of thickness h, in which the solvent diffuses, initially at the concentration C_0, and whose surfaces are kept at the uniform concentration C_1, the spatial and temporal evolution of the solvent concentration is given by

$$\frac{C-C_0}{C-C_0} = 1 - \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)}exp\left(-D\frac{(2n+1)^2}{h^2}\pi^2 \bullet t\right)\cos\left(\frac{(2n+1)\pi}{h}\right)$$

3

where D: diffusion coefficient; t: aging time; h: thickness of the plate

If we note M_s as the mass of water absorbed after an infinite time, then Eq. 3 is written as [24]:

$$\frac{M_t}{M_s} = 1 - \frac{8}{\pi}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}exp\left(-D\frac{(2n+1)^2}{h^2}\pi^2 \bullet t\right)$$

4

where M_t: the water content at time t; M_m: the maximum mass of water in equilibrium.

When M_t / M_m is less than 0.6, Eq. 4 becomes approximately [14]

$$\frac{M_t}{M_s} = \frac{4}{h}\sqrt{\frac{Dt}{\pi}}$$

5

When M_t / M_m is greater than 0.6, the equation describing the moisture absorption curve is [14]:

$$\frac{M_t}{M_s} = 1 - exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]$$

6

The diffusion coefficient D can be deduced from Eq. 5 as

$$D = \pi\left(\frac{k}{4M_m}\right)^2$$

7
where k is the slope of the linear part of the curve $Mt = (\sqrt{t}/h)$

2.4. Response surface methodology modeling

A statistical design of experiment, called Response Surface Methodology (RSM), allows process variables to be varied simultaneously, as compared to traditional testing, in order to derive the relationship among these variables. RSM offers a faster and more cost-effective method of collecting research findings than conventional experimentation with one variable as well as with a full variable [25–28]. In the current research, the effect of WF fiber content on the diffusion kinetics of HDPE/WF biocomposites by full immersion in distilled water at ambient conditions of the samples was investigated. The studied variables were fiber content (X1) and immersion time (X2). In Table 2, the variables and their corresponding values are reported. A two-factor central composite design (CCD) was used, involving 16 series of experiments in the RSM analysis, computed according to Eq. 8:

Table 2
Design of experiments for RSM model.

N°	Factors	Notation	Units	Levels		
				Low level	Intermediate level	High level
1	Immersion time	*Time*	hour	2	408	800
2	Content fibers	*W*	%	10	20	30

$$N = 2^k + 2k + k_c$$

8
In which N stands for the sum of experimental of tests to be performed with k standing for the number of parameters used and k_c stands for center-repeated series.. An experimental model was developed to correlate the response with the two factors in the process based on a quadratic polynomial model as indicated in Eq. 9.

$$Y = B_0 + \sum B_i X_i + \sum B_{ii} X^2 + \sum B_{ij} X_i X_j + E$$

9
In which Y represents the value of the predicted response, where B_0 is the constant value and B_i, B_{ii} and B_{ij} are the coefficients of the linear, quadratic and interactive terms, respectively [29].

The experimental plan and the measured response (% water absorption) for the two parameters and the 16 experimental runs produced are presented in Table 3. To perform the RSM regression analysis, the Design Expert software was used to optimize the biocomposite composition data generated with the input data. An ANOVA analysis including quadratic, linear and coefficient of interaction is carried out for the model’s statistical test using F-test for the empirical interrelationship of the input parameters and the output model. For testing the model fit performance, each individual term of the model was statistically tested, confirming F-value significance with $p < 0.05$. Also, in order to verify the goodness of the proposed polynomial, the R^2, the adequate accuracy and *predicted* R^2 and the *adjusted* R^2 values of the models were acquired. Both the response surface map and the contour map were constructed to display the input-output interactions.

Table 3
Experimental data with RSM and ANN model results for water absorption of HDPE/WF biocomposite.

Experiment number	Input variables		Output variables		
	WF (%)	Time (h)	EXP (%)	RSM (%)	ANN (%)
1	0	0	0.0000	0.0818	0.0002
2	10	2	0.4325	0.4064	0.4371
3	20	2	0.9013	0.9566	0.8985
4	30	2	1.6516	1.7378	1.6511
5	10	24	0.5627	0.4789	0.5552
6	20	24	1.0141	1.0457	1.0240
7	30	24	1.8308	1.8434	1.7763
8	10	48	0.6145	0.5543	0.6598
9	20	48	1.1251	1.1392	1.1659
10	30	48	1.9661	1.9550	1.9649
11	10	120	0.8504	0.7578	0.8471
12	20	120	1.4063	1.3970	1.4831
13	30	120	2.2632	2.2671	2.2359
14	10	288	1.1432	1.1000	1.1385
15	20	288	1.8832	1.8660	1.8694
16	30	288	2.9807	2.8628	3.0051
17	10	408	1.1431	1.2308	1.1030
18	20	408	2.0111	2.0873	2.0191
19	30	408	3.2515	3.1746	3.2532
20	10	572	1.1404	1.2565	1.1481
21	20	572	2.1448	2.2366	2.1438
22	30	572	3.4793	3.4476	3.4796
23	10	800	1.1408	0.9982	1.1395
24	20	800	2.1480	2.1503	2.1473
25	30	800	3.4801	3.5333	3.4417

2.5. Artificial neural network

To train the network, a multilayer perceptron (MPL) was used, and the algorithm of back propagation training was used for modelling. It consisted of an input layer, a hidden layer, and an output layer. In the input layer, the variables were the fiber content and the immersion time of the biocomposite in water, while, in the output layer, it was the water absorption. To determine the ideal neural number in the hidden layer, a test series of approaches was used to obtain the number of neurons that would yield the least root mean square error (RMSE) and the most correlation coefficient (R^2) [30–32]. This approach was intended to provide a minimum discrepancy in predicted and experimental outputs as well as reduce the opportunity for excessive model fitting. High as well as low neural numbers were omitted, as they cause complication in fitting and reduced rate of convergence, respectively [27, 33]. To train the network, 70% of the datasets were utilized. Of the remaining, 15% were utilized to test the network, and the other 15% were utilized for result validation.

The accuracy of the model given by ANN was validated by the values of correlation coefficient (R^2) and the mean squared error (*MSE*). The lower the values of *MSE*, the more precise the ANN model is in the prediction. The three parameters were given by equations 10–12 [34].

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left|\left(Y_{Predicted} - Y_{Experiment}\right)^2\right|$$

10

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_{Predicted} - Y_{Experiment}\right)^2}{\sum_{i=1}^{n}\left(Y_{Predicted} - Y_{Mean}\right)^2}$$

11

$$RMSE = \sum_{1}^{n}\sqrt{\frac{(X_{Predicted} - X_{Experiment})^2}{n}}$$

12

Results And Discussion

3.1. Water absorption

Figure 1 shows the weight gain M_t in percentage as a function of the square root of time of HDPE biocomposites reinforced with different rates of WF fibers (10, 20, and 30% by mass) immersed at room temperature. Several specimens of the investigated biocomposites immersed in water were weighed to compare the water absorption in biocomposites with different mass ratios of WF fibers. Each point represents the average value obtained from the measurements of three samples. Table 4 shows the absorption parameters (slope, diffusion coefficient and water absorption at saturation) that allow the Fick's law curve to be plotted. The calculated diffusion coefficients *D* (diffusivity along the thickness direction) of the three sample types are also different. It is also noticed that the percentage of water absorption is different for the three formulations. The test results showed that the water absorption process in WF-based biocomposites follows the Fickian model. A linear relationship between water uptake and the square root of time was observed, followed by the appearance of a plateau at saturation. The values of the plateau at saturation M_∞ are 1.14%, 1.74%, and 3.48% for the formulations: PEHD/10%WF, PEHD/20% WF, and PEHD/30%WF, respectively.

Table 4
Water absorption parameters of HDPE/WF biocomposites obtained using Fick law.

Biocomposites	**k**	*$D \times 10^{-6} (mm^2/s)$*	**M∞** *(%)*
PEHD/10%WF	0.00593	5.31	1.14
PEHD/20% WF	0.00973	6.14	1.74
PEHD/30%WF	0.01029	1.72	3.48

It is noted that the addition of WF fibers in the biocomposites reduced the diffusivity (5.31 x 10^{-6} mm^2/s for the HDPE/10% WF biocomposite and 1.72x 10^{-6} mm^2/s for the HDPE/30% WF biocomposite). The value of the diffusion coefficient for the HDPE/30% WF formulation obtained (1.72 x $10^{-6} mm^2/s$) was lower than that found by Malloum et al. [35] for the $[0/90]_S$ flax/epoxy biocomposite (38 x 10^{-7} mm^2/s). In contrast, the recorded diffusion coefficient (5.31x $10^{-6} mm^2/s$) for the HDPE/10%WF biocomposite was higher than that obtained by Mannan et al. [36] for raw jute fiber (3.38 x 10^{-7} mm^2/s). On the other hand, the diffusion coefficient values obtained experimentally for the different WF fiber masses in this study were lower than those found by Célino et al. [6].

Figure 1 **and** Table 4

3.2. Regression model development

From the 25 experimental series presented in Table 3, the polynomial equation coefficients as explained above were determined. The quadratic models for the actual values of the variables are presented in Eq. 12.

$$Waterabsorption = 0.081823 + 0.020240 \times \mathrm{W} + 0.002625 \times Time + 0.000075 \times W \times \mathrm{Time} + 0.001154 \times W^2 - 3.28831\text{E-}06 \times Time^2 \quad (12)$$

From the ANOVA results obtained by the regression model, it was found that the R^2 value was 0.9946, which indicated that there was 99.46% of variability in the data explained by the model. The R^2 value cannot be inferior to 0.75 in order to ensure the adequacy of a model [37–39]. The fitted coefficient of determination value ($Adj\ R^2$ = 0.9931) thus verified the high significance of the model, indicating adequate accord of the predicted and experimental values of the water absorption. Therefore, a good prediction adequacy of the model was achieved within the experimental range of the variables. Rai et al. [40] indicated that the difference between $Adj\ R^2$ and $pred\ R^2$ should be less than 20% to have good agreement. This specification is satisfied in the current research, as $pred\ R^2$ is 0.9829. So, the model provides 98.29% predictive variability in water absorption in the range of experimental conditions. In Table 5, the ANOVA for individual terms in the quadratic model was reported. For a term to be significant, the F value must be large and $P < 0.05$. According to Table 5, all linear terms W and Time, quadratic terms W^2 and $Time^2$, and interaction terms $WxTime$ were significant on the water absorption of HDPE/WF biocomposites.

Table 5
Analysis of variance for water absorption quadratic model.

Source	DF	SS	MS	F-value	P-value	Remarks
Model	5	21.52	4.30	696.49	< 0.0001	Significant
A-W	1	13.45	13.45	2176.04	< 0.0001	Significant
B-Time	1	5.93	5.93	959.52	< 0.0001	Significant
AB	1	0.7375	0.7375	119.34	< 0.0001	Significant
A^2	1	0.1600	0.1600	25.89	< 0.0001	Significant
B^2	1	0.9742	0.9742	157.64	< 0.0001	Significant
Error	19	0.1174	0.0062			
Total	24	21.64				
SD = 0.0786 Mean = 1.62 Coefficient of variation = 4.85%						R^2 = 99.46 R^2 adjusted = 99.31% R^2 predicted = 98.29% Adequate precision = 72.3044

In addition to the ANOVA, the normal probability plot and the actual compared to the predicted plots for water absorption values are also illustrated in Fig. 2a **and b** to test the assumptions of normality. The residuals are observed to fall along a fairly straight line, indicating the normally dispersed error as a function of immersion time, thereby proving the significance of the terms reported by the models expanded in Fig. 2c.

3.3. Individual parameters influence on water absorption of HDPE/WF biocomposite

The influence of the two process parameters, such as fiber content and immersion time on the water absorption of the different samples, was shown in Fig. 2 **(d-f)**. The chosen process variables had a considerable effect on the water absorption, revealing also that the water absorption was higher for a fiber content of 30% as well as for an immersion time of 800 hours (plotted in red) compared to that of 2 hours (plotted in black).

Figure 2 **and** Table 5

3.4. Analysis of HDPE/WF biocomposite water absorption response surface and 3D plots

Interactions of combination effects between inputs and response variables can also be studied using other plotting representations such as 3-D plots and surface contour plots [16, 41]. The plots are shown in Fig. 3, and they were used to explain the influences, from different parameters, on water absorption. These surface graphs were produced by changing the two variables in the range of the experimental test using the model. An interactive influence of fiber content and immersion time was illustrated. It was found that, with increasing fiber content and immersion time, the water absorption increased to saturation at a determined immersion time and subsequently reduced. This is related to the pore spaces allowing the passage of water. The lowest absorption was obtained for the HDPE/WF biocomposite with 10% fiber content. In the type of 3D plot, there was a significant interactive effect of fiber content and immersion time.

Figure 3

3.5. ANN modelling

The sample distribution that was utilized to model ANN consisted of 21 for training, 2 for validation, and 2 for testing (Table 6). In this study, the Levenberg-Marquardt algorithm was chosen for training the ANN model in predicting the water absorption of HDPE/WF biocomposite. A repeated configuration of the network was performed for training after the collection of input and target data was completed. The architecture of the ANN network, which was composed of three layers: input, hidden and output, was illustrated in Fig. 4a. The training operation and the validation were terminated at 11 iterations, as seen in Figs. 4b and 4c, once an optimized validation was recorded at 0.0041767 by the gradient at the eleventh iteration. ANN considered this stopping point as an optimum point. Over this point, the validation bias passed the acceptable tolerances. By means of errors, a histogram of errors distributed on a 20-bins interval produced in the model network during training, validation, and tests were generated, as illustrated in Fig. 4d. The ANN results of the modeling process are plotted in Fig. 5 against the actual data for the HDPE/WF biocomposite throughout the training, validation, and testing. Experimental data variability is reflected by the determination coefficient R^2, which indicated the prediction level of the model [32]. The correlation accuracy levels for training, validation, testing, and total are 0.9955, 0.9999, 0.9915 and 0.9957, respectively, providing confidence in the resulting model. The predicted values by the ANN approach closely to the threshold of parity, they agreed well with those determined experimentally. Therefore, a reliable prediction of the water absorption of HDPE/WF biocomposites can be carried out by using the ANN technique.

Table 6
ANN composition of the study samples.

	Samples	R	MSE
Training	21	0.9997	0.000663
Validation	2	0.9988	0.00356
Testing	2	0.9671	0.0220

Figure 4 **and** Table 6

3.4. Benchmarking of model performance

The predicted results of the two models (ANN and RSM) and those experimentally observed are shown in Table 3 and Fig. 6a. It is found that these models satisfactorily describe the experimentally observed findings, thereby ensuring a good simulation of the experiments. RSM model error percentages in predicting water absorption were observed to be higher than those of the ANN model, as seen in Fig. 6b, leading to the conclusion that the ANN model offers more accurate prediction than the RSM model. Since the percent error is low, the optimization procedure is suitable for the model predictions and is considered to be highly effective.

Figure 6

3.5. Optimization process by RSM

RSM was used to optimize the water absorption process. The objective was to evaluate the highest absorption capacity given the experimental requirements. The desirability function for the best predictive model from the optimization process was used for this purpose (Figs. 7 and 8). The parameters and ranges for the optimization were the fiber content (10 to 30%) and the immersion time (2 to 800 hours). The best fit for immersion time and fiber content for a maximum, within range and minimum absorption was found to be 686.70 hours and 29.81%, 83.30 hours and 22.63%, and 2 hours and 10.26%, respectively (Table 7). The optimum value of 1.83 was obtained for water absorption. This was confirmed by the contour plot and the 3D plots.

Table 7
RSM-based response optimization.

Number	Time (h)	W (%)	Absorption WA (%)	Desirability	
Goal: maximize absorption					
1	**686.682**	**29.814**	**3.508**	**1.000**	**Selected**
2	743.640	29.684	3.498	1.000	
3	692.090	29.611	3.481	1.000	
4	800.000	30.000	3.533	1.000	
5	696.858	29.702	3.495	1.000	
Goal: limit absorption max-min					
1	**83.298**	**22.631**	**1.469**	**1.000**	**Selected**
2	408.000	20.000	2.088	1.000	
3	24.000	20.000	1.046	1.000	
4	572.000	30.000	3.449	1.000	
5	408.000	10.000	1.230	1.000	
Goal: minimize absorption					
1	2.000	10.000	0.407	0.883	
2	2.000	10.103	0.411	0.882	
3	**2.001**	**10.262**	**0.418**	**0.880**	**Selected**
4	2.001	10.455	0.427	0.877	
5	2.001	10.767	0.441	0.873	

Figure 7,8 **and** Table 7

Conclusion

The influence of fiber content and immersion time on the water absorption of HDPE/WF biocomposite was investigated. The experiments were performed by using the CCD method of RSM. In this study, the modelling and optimization of the water absorption were detailed. Many relevant conclusions were obtained from this study. The water absorption was noticed to increase with increase in the fiber content of WF fibers as well as with the immersion time. The absorption phenomenon was rapid in the first phase of the tests, reaching the saturated level after 408 hours of immersion. The ANOVA results showed that the quadratic model was statistically significant for the HDPE/%WF biocomposites. This is due to the p values being less than 0.05 and the F value being greater than F_{cri}. The RSM predicted value results satisfactorily describe those obtained experimentally. A good tool for modeling to help in the identification of main the significant factors, as their interacting was the response surface methodology (RSM). The optimal values of the fiber content and immersion time for a maximum, minimum and within range absorption process were found to be 686.70 hours, 29.81%, 2 hours, 10.26%, and 83.30 hours, 22.63%, respectively, for the developed HDPE/WF biocomposite. Therefore, the RSM approach can reliably predict the water absorption of HDPE/WF biocomposites.

Declarations

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Author contribution

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Consent for publication The authors consent to publish.

Code availability Not applicable

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Figures

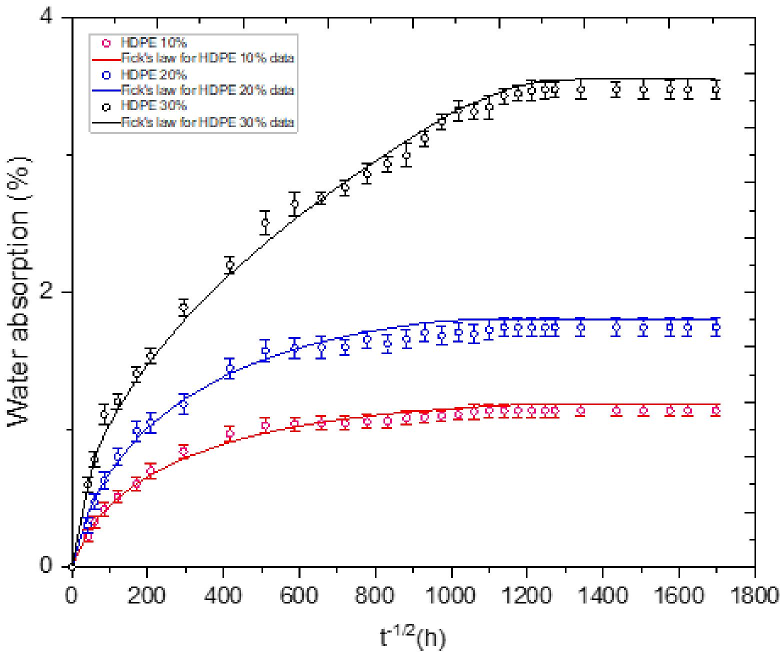

Figure 1

Evolution of water absorption as a function of the square root of time at different WF fiber mass ratios of HDPE/WF biocomposite.

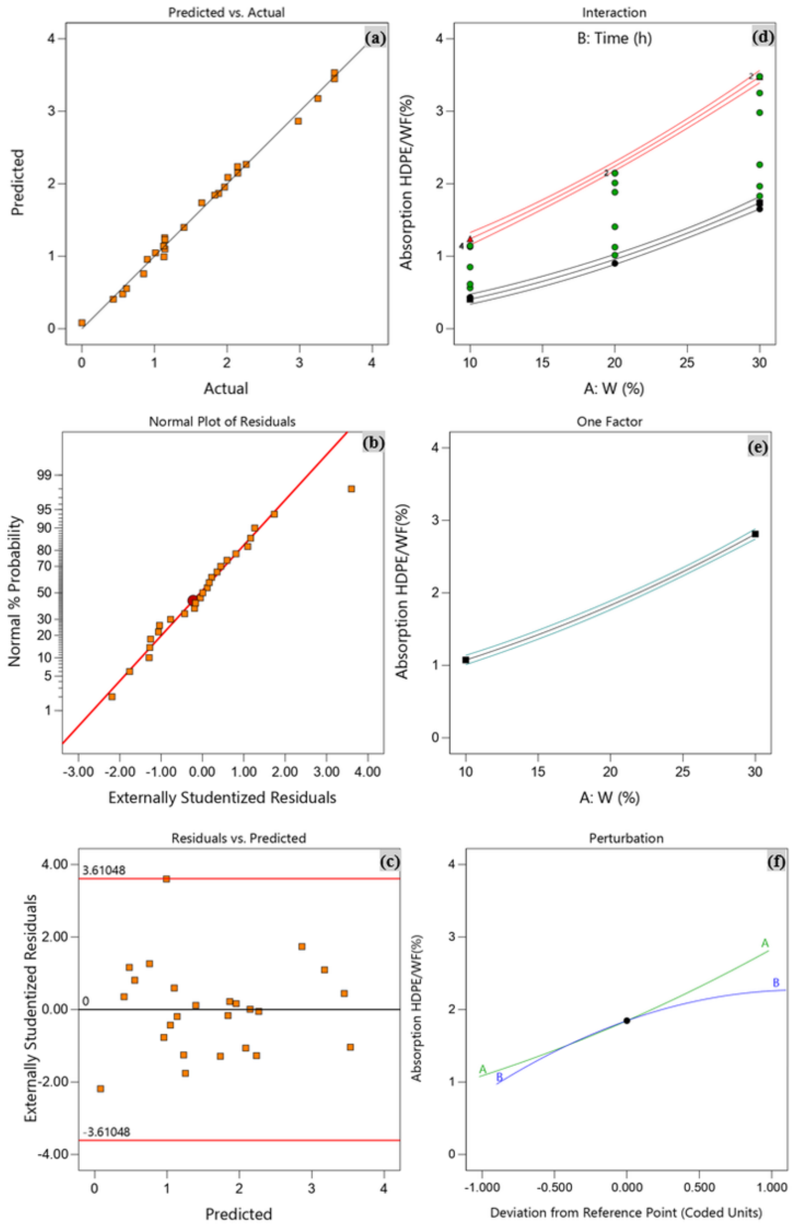

Figure 2

RSM diagnostic plots (a). Predicted vs. actual values, (b) Normal probability distribution, (c) The distributed residuals of HDPE/WF biocomposites, (d) immersion time effect (e) fiber content effect (f) Disruption

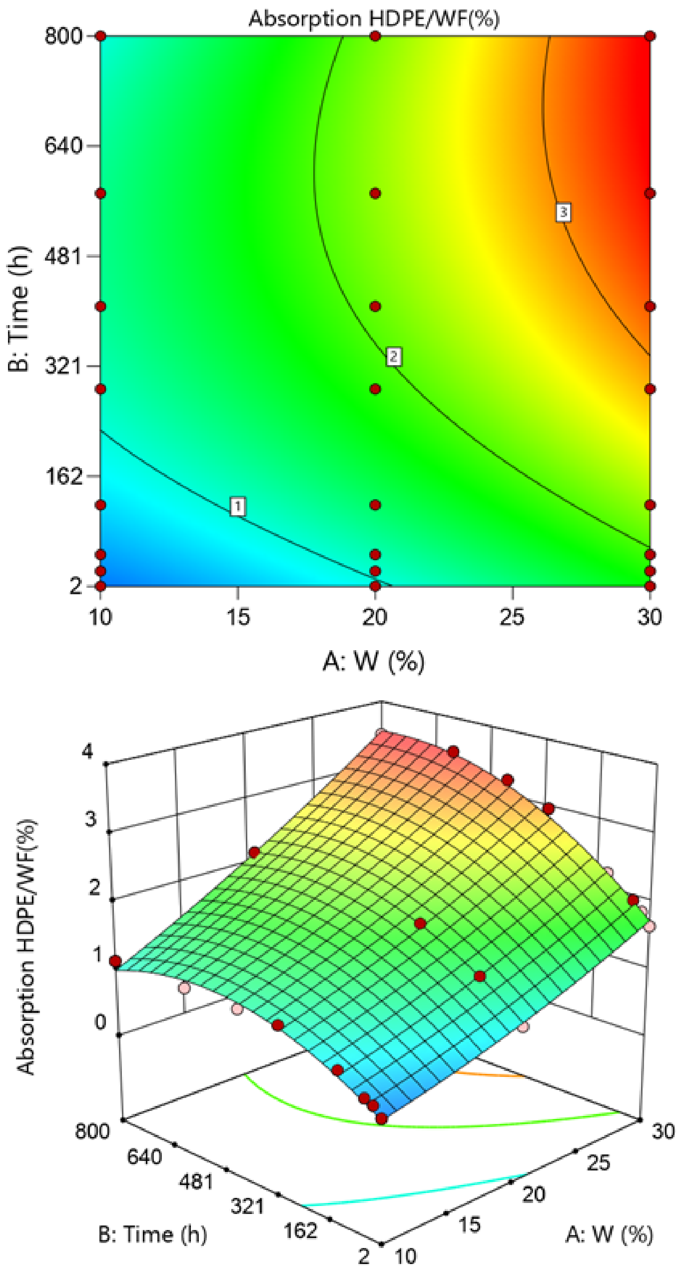

Figure 3

Plots of (a) Surface contour and (b) 3D output experimental design as a function of fiber content and immersion time.

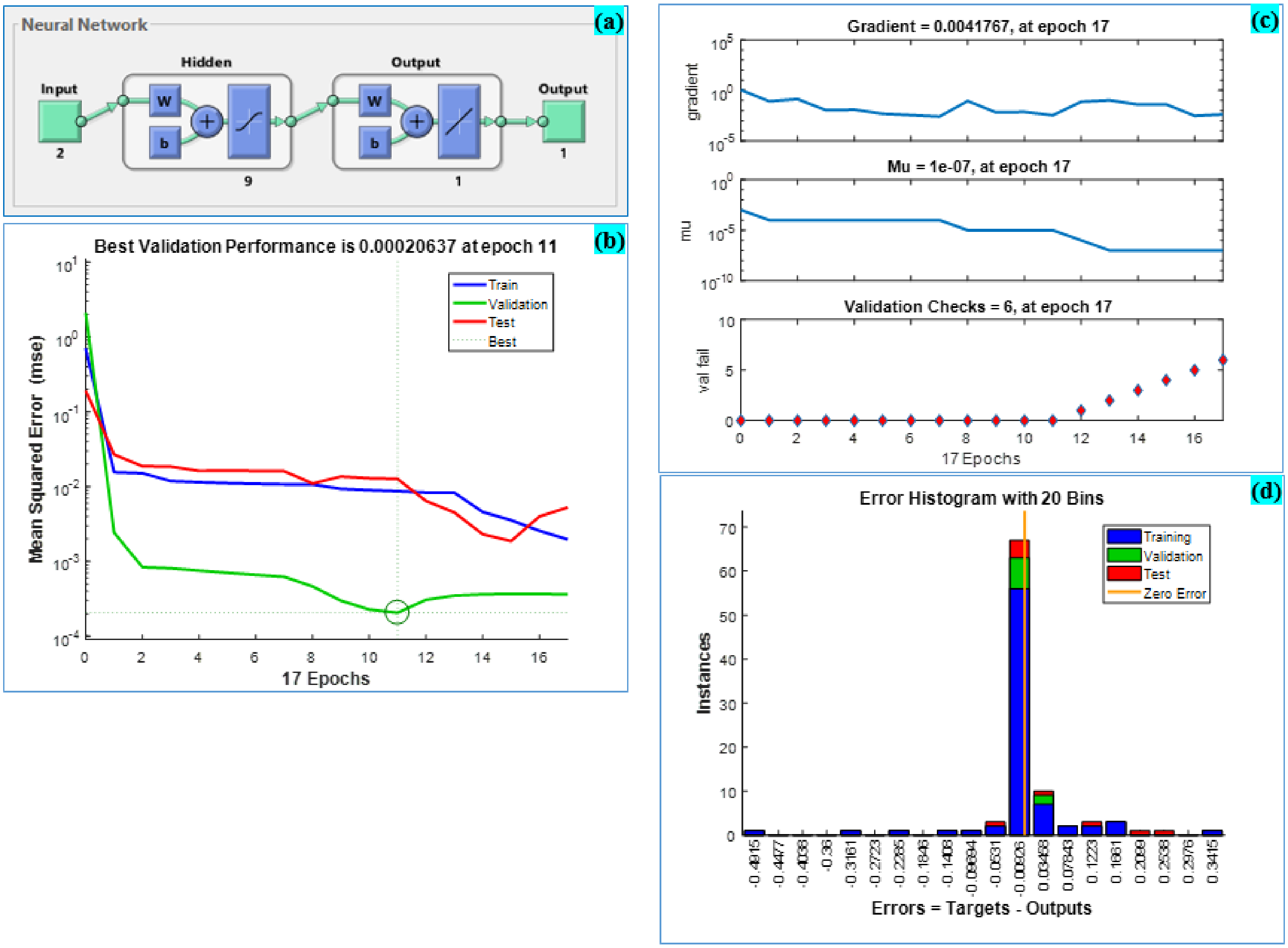

Figure 4

Plots of the water adsorption process used in this investigation (a) ANN architecture, (b) the mean square error as a function of the test periods, (c) Illustrates of training conditions and (d) Error residuals for water absorption of HDPE/WF biocomposites.

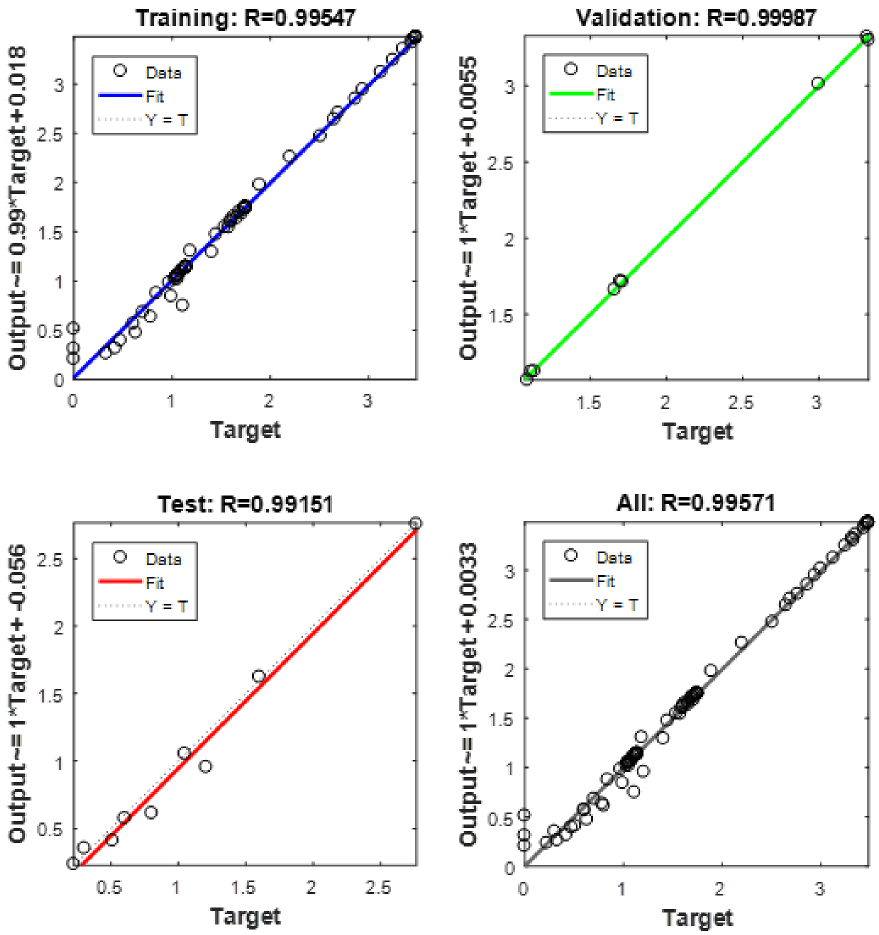

Figure 5

Correlation between experimental data with the obtained ANN results.

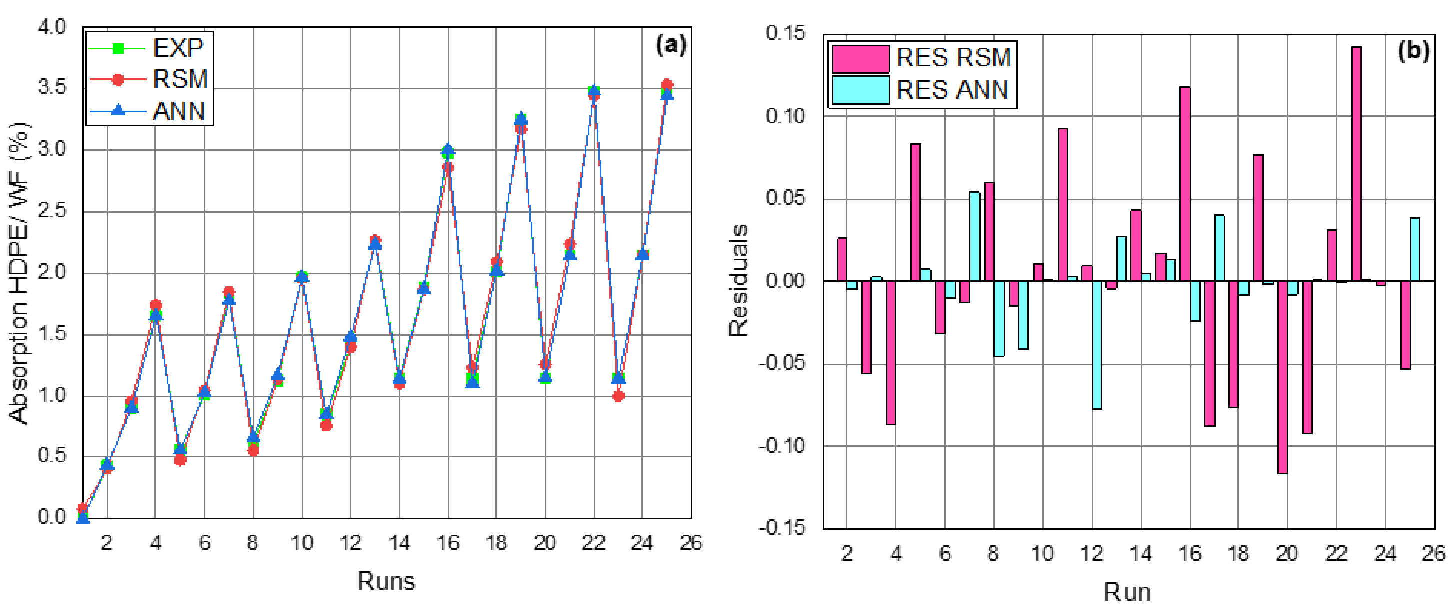

Figure 6

Comparison of RSM and ANN predictive values of HDPE/WF biocomposites (a) models and (b) residual errors.

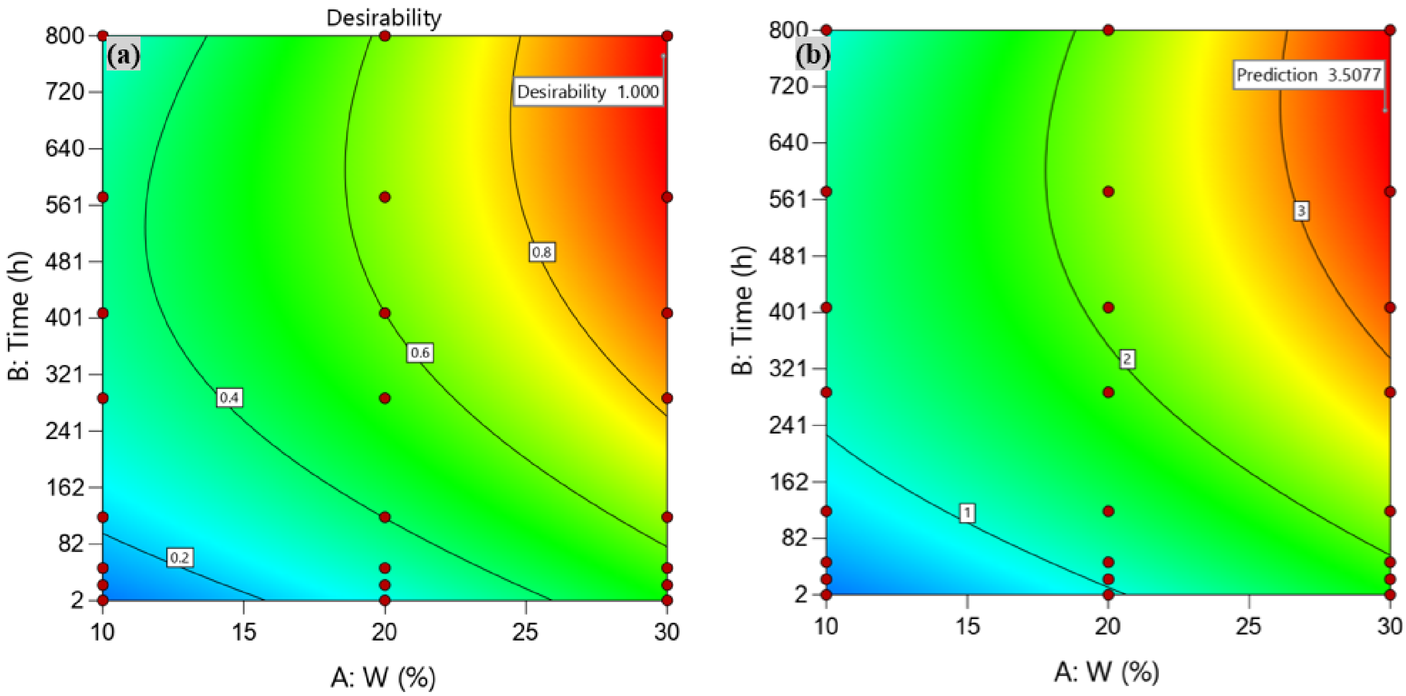

Figure 7

Surface contours of (a) desirability and (b) optimal prediction for a maximum water absorption.

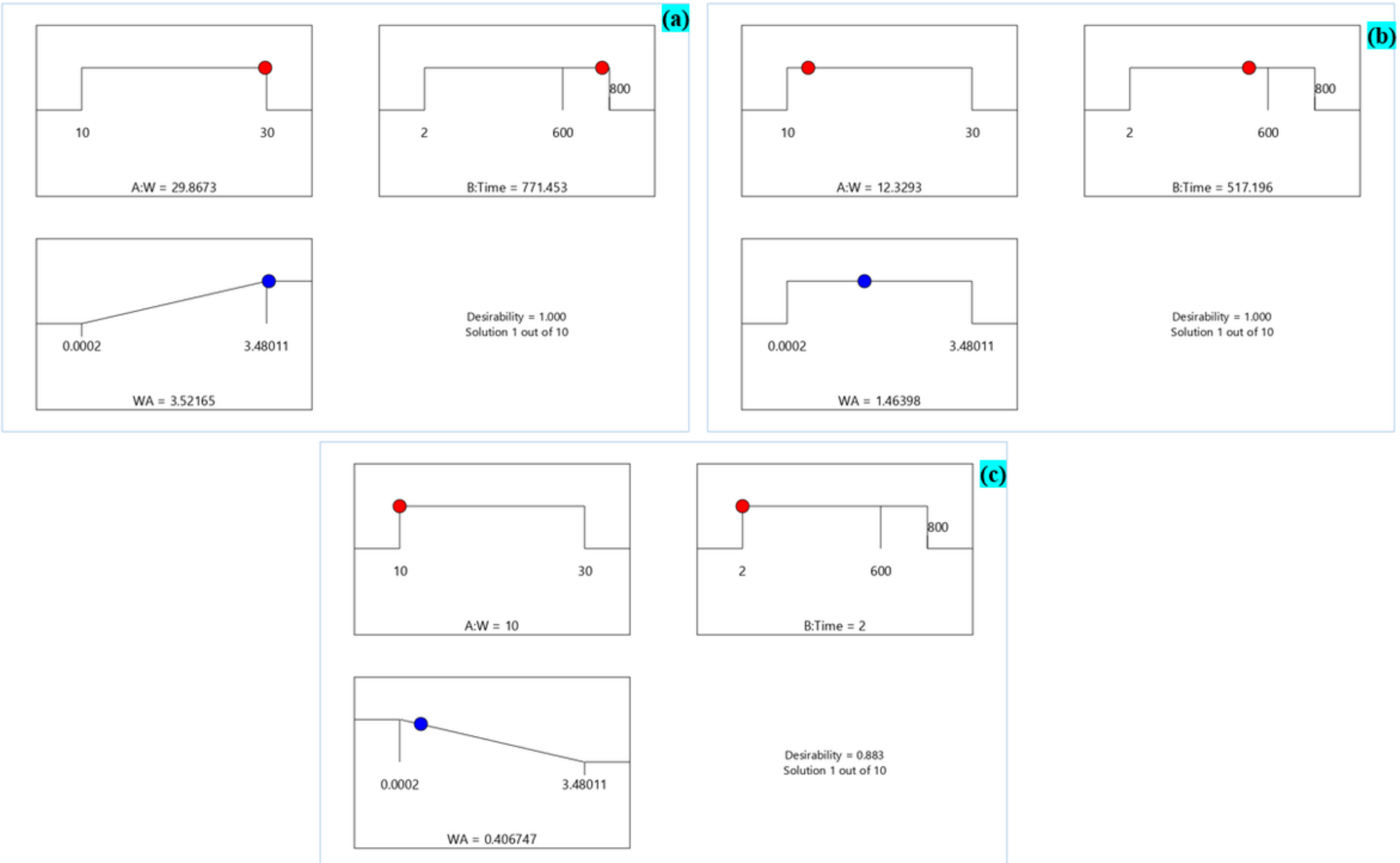

Figure 8

Desirability diagram of HDPE/WF biocomposite absorption (a) maximum, (b) within range and (c) minimum.