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Original Research Article

Kenaf Derived Cellulose (KDC)/Poly(lactic acid) (PLA) Composites: Optimisation of Melt Mixer Parameters via Response Surface Methodology

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Abstract: Kenaf-derived cellulose (KDC) reinforced poly(lactic acid) (PLA) composites with constant filler loading of 5% KDC were prepared by melt compounding and compression moulding. Kenaf bast fibre was chemically treated by chlorination and mercerisation to obtain the α-cellulose and evaluated as the KDC. Mixer variables, namely mixing temperature (160 to 180°C) and mixing time (10 to 30 min), were screened and optimised with the response surface method (RSM) to maximise the tensile strength, minimise the stock temperature (below 200°C to avoid fibre degradation) and monitoring the mixing torque curves (to ensure composite is well mix at sufficient duration). The variables were selected as two independent variables, whereas the tensile strength and stock temperature were selected as the response variables in this response surface study. The mixing temperature term was significant, with a P value less than 0.0500 for both tensile strength and stock temperature. The optimum variables were determined at 170ºC and 30 min based on the overlaid contour of tensile strength, stock temperature, and stabilisation zone via mixing torque of composites at various loading.

Keywords: Melt compounding; Mixing torque; Tensile strength; Poly(lactic acid); Derived cellulose

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1. Introduction

The use of biopolymers as an alternative to conventional plastics in packaging has increased due to their biodegradability, sustainable raw materials, and comparable processing characteristics to those of existing thermoplastics (Torres-Giner *et al.*, 2021). Biopolymers' characteristics, such as ease of handling, reliability, chemistry, biocompatibility, non-toxic, and eco-friendly, enable them to be used in various applications, including food packaging, agriculture, biomedical, pharmaceuticals, ecological, and aqua treatment, among others (Das *et al.*, 2023; Udayakumar *et al.*, 2021). Different types of biopolymers can be derived from renewable sources. Among the examples of biopolymers are polylactic acid (PLA), poly (vinyl alcohol) (PVA), polybutylene succinate (PBS), starch, cellulose, chitosan, alginate, and gelatine (Babaremu *et al.*, 2023; Juikar & Warkar, 2023; Dutta & Sit, 2024). Among these, PLA is a promising candidate to replace petroleum-based plastics due to its renewable nature, good transparency, excellent mechanical properties, and thermal stability (Trivedi *et al.*, 2023), and comparable to conventional polymers such as polypropylene (PP), polystyrene (PS), polyethylene (PE), and polyethylene terephthalate (PET) (Mehmood *et al.*, 2023). PLA characteristics can be significantly enhanced by producing biocomposites that reinforce the PLA matrix with various natural fibres, as indicated in numerous existing literature (Ferdinánd *et al.*, 2023; Trivedi *et al.*, 2023). The primary function of fibre in composites is to enhance strength and thickness. Meanwhile, a polymer matrix like PLA binds the fibres together, protecting them from damage and improving their toughness and resistance to heat and corrosion (Yallew *et al.*, 2020). The combination of these materials can produce biocomposites that are both environmentally friendly and exhibit desirable functional characteristics (Kumar *et al.*, 2023).

The current development of biodegradable composite materials has been performed with various natural fibres such as kenaf, flax, sisal, jute, and bamboo (Kumar *et al.*, 2021). In general, natural fibres offer numerous benefits compared to synthetic fibres, including high strength and elasticity modulus, renewability, easy accessibility, cost-effectiveness, low density, low energy needs, reduced industrial fuel expenses, high acoustic damping, and the ability to decompose (Ahmad & Zhou, 2022; Mohammed *et al.*, 2024). Among the natural fibres, Kenaf fibre (*Hibiscus cannabinus L.*) has demonstrated high potential as reinforcement in PLA. Kenaf fibre was reported to have affordable prices in Malaysia because of the plentiful local supply, making it an ideal option for biocomposites (Alaa *et al.*, 2023). Kenaf plant fibre contains approximately 56% cellulose in the bast and 46% in

the core (Khan *et al.*, 2023). Numerous studies have reported that kenaf bast fibres exhibit remarkable mechanical properties, including flexural and tensile strength (Haryati *et al.*, 2021), making them suitable as reinforcing elements to replace glass fibres in polymer composites (Hazrol *et al.*, 2021). In a study by Marzuki *et al.* (2019), reinforcing kenaf bast fibres into composites results in enhanced mechanical properties (tensile strength, elongation at break, and toughness) compared to the kenaf core fibre composite. The study also reported that high fibre loading decreased both tensile and elongation at break while increasing the impact strength of the composites. Furthermore, studies have indicated that increasing the loading of kenaf fibre up to 70 wt% has shown to have better wear resistance compared with oil palm fibre (Shuhimi *et al.*, 2016). Other advantages of kenaf fibre reinforcement include renewability, biodegradability, cost-effectiveness, eco-efficiency, and improved thermal properties (Adole *et al.*, 2019).

Previously, a wide range of studies has been conducted on the reinforcement of natural fibres into biocomposites (Singh & Mohapatra, 2024; Soćko & Andrzejewski, 2024). Extensive literature surveys on these studies have addressed issues such as improper processing methods, insufficient adhesion between the fibres and the polymer, poor wettability, and the formation of voids. These issues significantly impact the mechanical properties of the composites (Tharazi *et al.*, 2017; Owen *et al.*, 2024; Ashothaman *et al.*, 2024). Thus, suitable processing parameters must be carefully selected to obtain the optimum composite products. In this study, melt compounding was used to produce kenaf-derived cellulose (KDC)/PLA composites due to its versatility, cost-effectiveness, environmental-friendliness, and suitability for large-scale production (Verma & Goh, 2019). The main processing parameters in melt compounding include temperature, mixing speed, and time (Ketabchi *et al.*, 2019). In a study by Yallew *et al.* (2020), process parameters such as heating temperature, compressive pressure, and moulding time were studied to fabricate natural fibre-reinforced polypropylene composites based on natural fibres from hemp, sisal, and jute. Sisal fibre was found to be more efficient in improving the bio-composite's strength than the jute and hemp fibres. The highest tensile strength can be observed at 175ºC and 1 MPa, while the lowest tensile strength was obtained at 185ºC and 1.5 MPa. Singh *et al.* (2021) have studied the effect of moulding temperature (160–180ºC) and fibre volume fraction (25–50%) on the mechanical properties of flax fibre-reinforced PLA composites. The maximum tensile and flexural strength was obtained at the moulding temperature of 170ºC with a 35% fibre volume fraction.

Processing parameters are essential for achieving the desired properties of biocomposites. However, there remain limited studies on processing PLA-based biopolymer composites reinforced with kenaf fibres. In addition, work has yet to be conducted on optimising the melt compounding parameters of KDC/PLA to obtain optimal torque and stock temperature (temperature of the blend in the mixing chamber). Torque and stock temperature are critical parameters that must be monitored during processing. It is essential to control or reduce the torque to ensure adequate mixing and minimise mechanical wear. Additionally, the stock temperature should not exceed a specific range to prevent sample degradation (Tee *et al.*, 2014) . Thus, this study aims to optimise the processing parameters (temperature and time) to maximise the tensile strength, minimise the stock temperature, and monitor the mixing torque curves of KDC/PLA composites using a response surface methodology (RSM) with a central composite design (CCD). RSM integrates mathematical and statistical techniques for the analysis, modelling, and optimisation of processes. The main advantage of using RSM is its capability to minimise the number of trials, thereby reducing both experimental time and costs. Moreover, it helps to predict the interaction between variables (Wu *et al.*, 2018). The melt compounding was conducted by reinforcing a fixed amount of KDC (5%) into PLA. The optimisation of temperature (160–180°C) and time (10–30 min) was carried out by analysing the tensile strength and mixing torque curves. The mixing torque curves can be analysed by monitoring both the maximum mixing temperature (kept below 200°C to prevent fibre degradation) and the stabilisation zone (to ensure thorough mixing over sufficient duration).

2. Materials and Methods

2.1. Materials Preparation

PLA 2002D (specific gravity of 1.24, melt temperature of 150–160ºC, glass transition temperature of 5ºC), purchased from NatureWorks LLC, USA, was employed as the polymer matrix. Kenaf bast fibre was kindly provided by the Institute of Tropical Forestry and Forest Products (INTROP), Malaysia, and was used as reinforcement and to prevent thermo-oxidative degradation of PLA biocomposites. This type of fibre (bast) was removed from the kenaf stem by the water retting process. Chemicals such as reagent grade sodium hydroxide (NaOH), acetic acid (CH_3COOH), and technical grade sodium chlorite ($NaClO_2$) with 80% purity were purchased from Fisher Chemicals Sdn. Bhd., Malaysia, and were used for the chemical treatment of fibres. The overall research flow chart, starting from material preparation until response surface analysis, is shown in Figure 1.

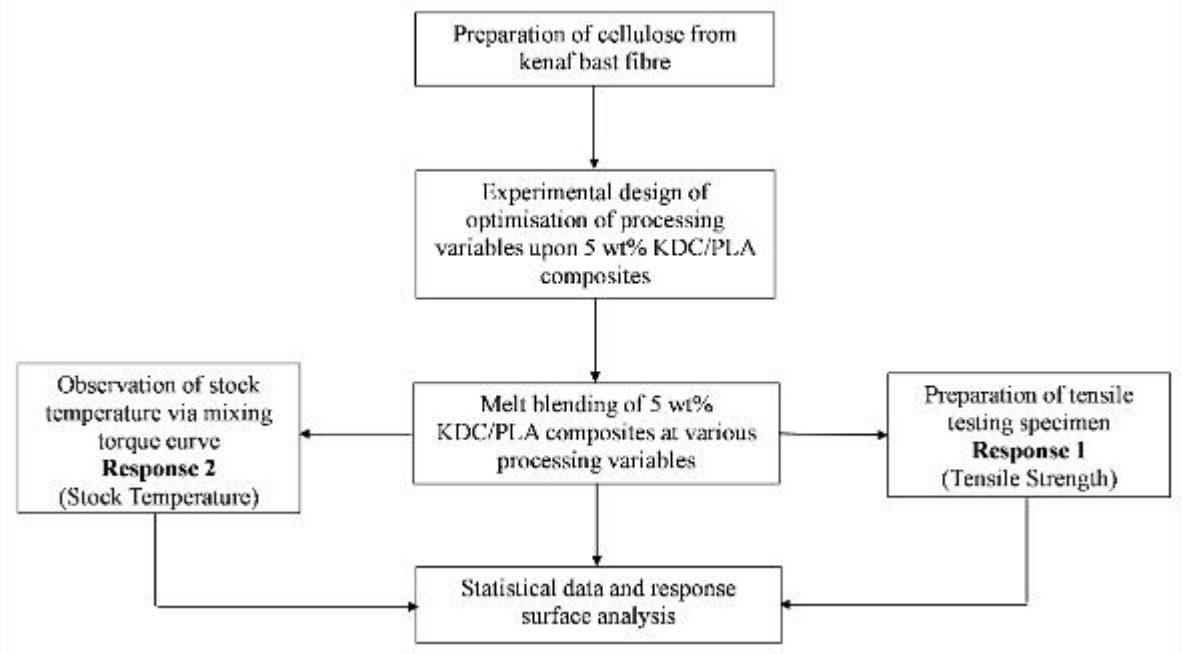


Figure 1. Process flow chart

2.2. KDC Preparation

The preparation of KDC involves two steps (Penjumras *et al.*, 2014). The first step was the production of holocellulose via the chlorination or bleaching process. First, 2.5 g of kenaf fibres were rinsed with tap water, followed by soaking in 80 mL of hot distilled water. Then, the mixture was heated in the water bath at 70°C. Next, 0.5 mL of acetic acid and 1 g of sodium chloride were added at hourly intervals for a total of 5 h. The changes in fibre colour from light brown to white indicated the occurrence of the delignification process. Subsequently, the fibres were thoroughly washed and rinsed with tap water. The second step involved the mercerisation process in which holocellulose was converted to cellulose. The holocellulose was treated with 10 mL of NaOH solution (17.5%) and heated in a water bath at 20°C. After 5 min, 5 mL of NaOH solution was added to the mixture 3 times at 5 min intervals. The mixture was left to stand for 30 min, resulting in a total treatment time of 45 min. Next, 30 mL of distilled water was added, and the mixture was allowed to stand for another 1 hr before filtration. Afterwards, 100 mL of NaOH solution (8.3%) was added to the cellulose for a duration of 5 min, followed by rinsing with water. For neutralisation, the alkaline cellulose was treated with 10% acetic acid for 5 min. Finally, the cellulose was filtered, washed, and rinsed with distilled water for the complete removal of acid. The cellulose was dried overnight in a vacuum oven at 100–105°C.

2.3. Preparation and Testing of Composites

The KDC was ground using a grinder by Huang Chuan Machinery, China, into smaller sizes and passed through a 500 µm sieve to obtain a uniform size. To achieve optimal mixing conditions, tensile strength (TS) was performed on 5 wt% KDC/PLA composites produced at different temperatures: 160, 170, and 180°C, and at various times: 10-, 20-, and 30-min. Mixing torque curves were simultaneously obtained during the process to monitor the actual temperature of the blend during mixing. These composites were produced using an internal mixer, Brabender Plastograph, Germany, at a fixed screw speed of 50 rpm. By employing the processing condition at 170°C for 30 min, composites at different KDC fibre loading ranging from 0–60 wt% were produced. Each composite was hot pressed at a temperature of 160ºC for 10 min. Figure 2 shows the overall preparation process for KDC/PLA composites. Tensile strength was measured using an Instron Universal Testing Machine Model 4301, USA, with a load cell of 1 kN. Each tensile and flexural test was performed at cross-head speeds of 5 and 1.3 mm/min, respectively, according to ASTM 1882L, until failure occurred. A minimum of seven specimens were tested for these purposes.

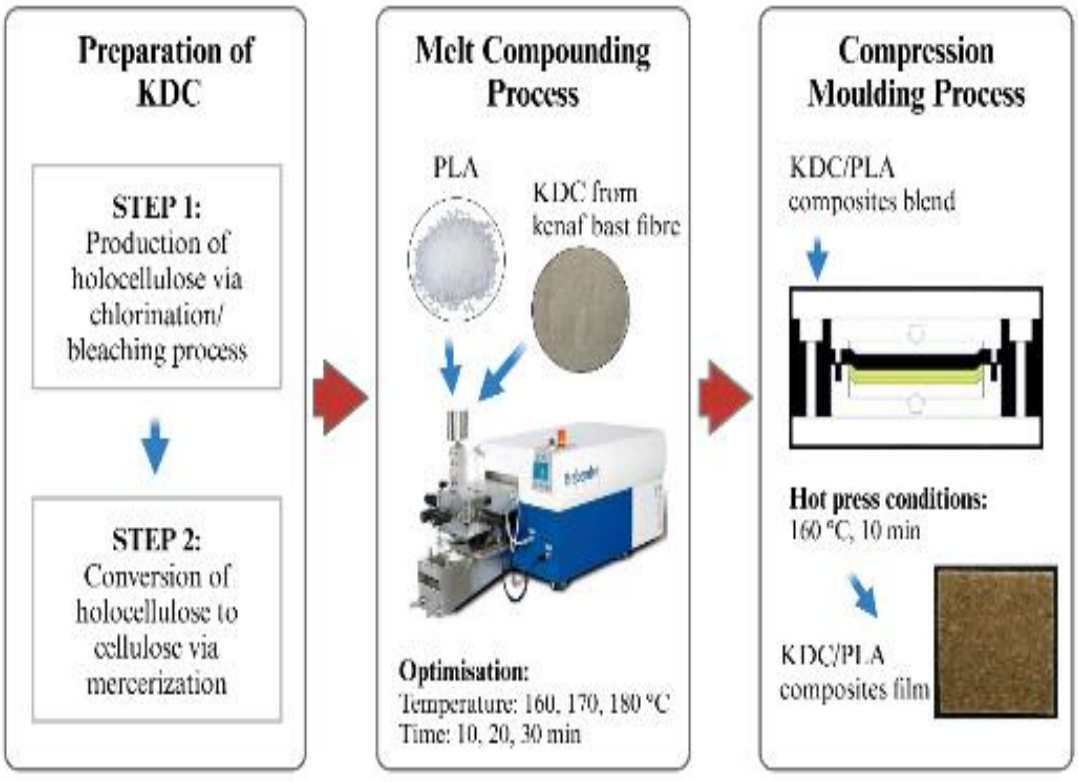


Figure 2. Schematic diagram of the KDC/PLA composites preparation.

2.4. Experimental Design

2.4.1. Central composite design (CCD)

RSM using central composite design (CCD) was applied to develop a mathematical relation between two independent variables, A and B, to the responses of tensile strength (MPa) and stock temperature (ºC). RSM was employed to optimise the level of significant mixing parameters using MINITAB® Release 14 (Minitab Inc., US) software. The CCD was chosen, which involves two factors (independent variables), and both factors are at three levels (Table 1), with five replications at the centre points (170ºC and 20 min), leading to a total of 13 sets of experiments (Table 2). The tensile strength of the KDC/PLA composite and the stock temperature represent the responses (dependent variables). The independent variables were concentrated on temperature and time, as denoted by A and B, respectively.

Table 1. Factor and corresponding levels for response surface design.

Factor	ID	Unit	Level		
			Low (-)	Medium	High (+)
Temperature	A	ºC	160	170	180
Time	B	min	10	20	30

2.4.2. Statistical analysis

Experimental data were fitted for regression analysis and to determine the regression coefficients. The statistical significance of the developed models was evaluated by the analysis of variance (ANOVA) test. The performance of the response surface was investigated by using the regression polynomial equation. The generalised polynomial model proposed can be expressed as,

$$Y = -\beta_0 + \beta_1 A + \beta_2 B - \beta_{11} A^2 - \beta_{22} B^2 - \beta_{12} AB \quad (1)$$

where is the desired response, β0 is the constant term, β1, and β2 are the regression coefficients for linear effect terms, β11, and β22 are quadratic effects, and β12 is the interaction effects. In this model, A and B are the process variables.

The adequacy of the models was determined using model analysis, the lack-of-fit test, and coefficient of determination (R^2) analysis. The experimental design matrix, data analysis, and optimisation procedure were carried out using MINITAB® Release 14 (Minitab Inc., US) software.

3. Results and Discussion

3.1. ANOVA and Regression

Experiments with various combinations of the mixing temperature and mixing time were carried out using data produced by the CCD. The experiment results are tabulated in Table 2.

Table 2. Central composite design (CCD) and corresponding test results.

	Factor		Response	
Treatment	**Temperature (A; ºC)**	**Time (B; min)**	**Tensile Strength (Y; MPa)**	**Stock Temperature (Z; ºC)**
1	160	10	55.61	188
2	160	20	58.41	188
3	160	30	57.11	188
4	170	10	58.15	197
5	170	20	59.41	196
6	170	20	60.71	196
7	170	20	63.52	196
8	170	20	62.53	196
9	170	20	59.84	196
10	170	30	60.57	194
11	180	10	59.30	203
12	180	20	59.70	203
13	180	30	57.22	203

Using the data from Table 2, several analyses were conducted. The model equation was fitted with both the independent variables and responses. The goodness of fit was determined using ANOVA and the coefficient of determination (R^2). The equations for the predictive models for tensile strength and stock temperature are presented in Equation (2) and Equation (3), respectively, in terms of coded factors. A and B refer to the temperature and time, respectively.

$$\text{Tensile Strength} = +61.19 + 0.85 *A - 2.10 *A2 - 1.80 *B2 \quad (2)$$

$$\text{Stock Temperature} = +195.69 + 7.50 *A - 0.50 *B \quad (3)$$

The experimental results obtained are analysed by analysis of variance (ANOVA) to measure the precision of the model (Nouri *et al.*, 2024). ANOVA of the response surface was made for tensile strength and stock temperature, respectively. The results of both responses are shown in Tables 3 and 4. For tensile strength response (Table 3), the ANOVA

data show that linear and quadratic terms were significant (P value <0.0500) at a 95% confidence level, while the interaction term was non-significant. However, only the linear term of stock temperature was significant (Table 4). This analysis indicated that the independent variables individually affected the response variable.

Table 3. ANOVA for tensile strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	44.332	44.332	8.8663	6.81	0.013
Linear	2	4.882	21.762	10.8812	8.35	0.014
Square	2	36.245	36.245	18.1226	13.92	0.004
Interaction	1	3.204	3.204	3.2041	2.46	0.161
Lack-of-Fit	3	2.606	2.606	0.8688	0.53	0.683
Total	12	53.448				

Table 4. ANOVA for stock temperature.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	339.597	339.597	67.919	149.87	0.000
Linear	2	339	339	169.5	374.01	0.000
Square	2	0.597	0.597	0.298	0.66	0.547
Interaction	1	0	0	0	0	1.000
Lack-of-Fit	7	3.172	3.172	0.453		
	3	3.172	3.172	1.057	*	*
Total	4	0	0	0		

The variables were then analysed to obtain a regression coefficient that could predict the response under a given range. The coefficient values were calculated, and the P values of all terms and interactions were summarised in Table 5. MINITAB® software generated a regression model consisting of 1 offset term, 2 linear terms, 2 quadratic terms, and 1 interaction term. The variable with the largest effect is mixing temperature, with a significant P value (0.014) for tensile strength and (0.000) for stock temperature. However, the mixing time term and the interaction term seem to be non-significant. It was found that the P value obtained for the regression model was very small for tensile strength (0.013) and stock temperature (0.000), in comparison with the desired significant level (0.0500). This indicates that the regression model accurately describes or predicts the pattern of significance for the responses. Besides, the values for the coefficient of determination (R^2) were (0.8296) and (0.9960), which indicate the adequacy of the applied model.

Table 5. Summary of regression coefficients for tensile strength and stock temperature.

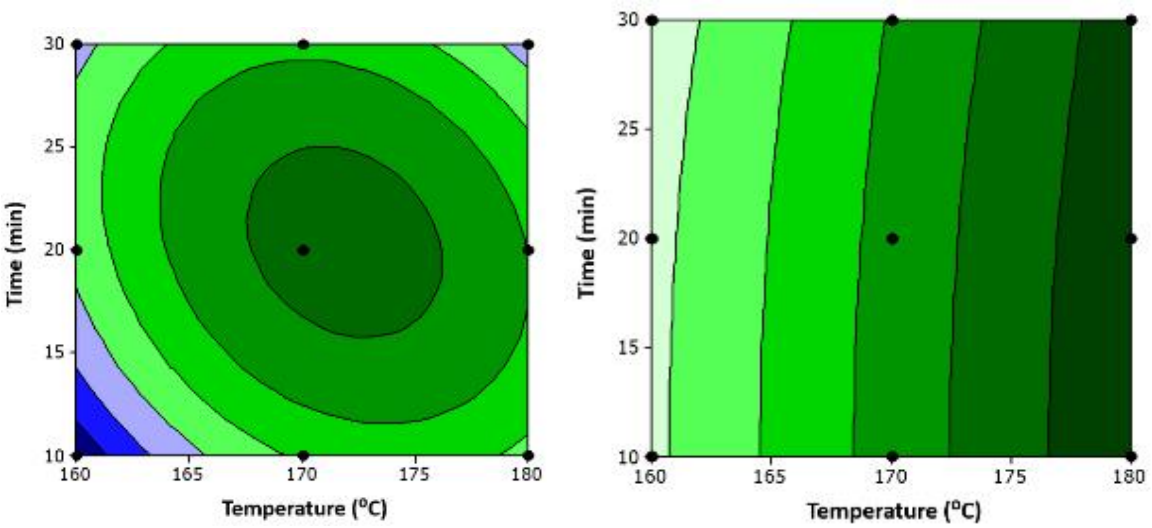
Source of Variance	P Value	
	Tensile strength (MPa)	Stock temperature (ºC)
Constant	0.017	0.000
A	0.014	0.000
B	0.057	0.112
A^2	0.016	0.544
B^2	0.030	0.544
AB	0.161	1.000
R^2	0.8296	0.9960

3.2. Tensile Strength

The contour plot shows the relationship between the response variables and factors based on the model equation. The contour plot represents two dimensions, which is the functional relationship between the response and factors. Points that have the same response (same tensile strength of stock temperature value) are connected to produce contour lines of constant value. As seen in Figure 3(a), the contour areas represent constant values corresponding to the tensile strengths of 56, 57, 58, 59, 60, and 61 MPa. The contour in the middle indicates the highest tensile strength (> 61 MPa). This plot suggests that the tensile strength reached a maximum value approximately at a temperature and time ranging from 170 to 175°C and 15 to 25 min, respectively. However, the tensile strength appeared to drop slightly at a mixing temperature of 180°C and at a longer mixing time. This is because heat treatment can induce several microstructural changes, such as crystallisation, that significantly influence the mechanical properties of the KDC/PLA composites. The processing temperature around 170ºC is optimal for PLA crystallisation, which improves its mechanical properties, including tensile strength. Thus, exceeding this temperature range can cause excessive crystallisation or thermal degradation, leading to a reduction in tensile strength (Goutianos & Beauson, 2023). In addition, weak fibre-matrix interfacial bonding was observed at a higher processing temperature due to the thermal degradation of the materials (PLA and fibre) (Tharazi *et al.*, 2017b; Singh *et al.*, 2024). This result agrees with studies by Singh *et al.* (2021) and Singh *et al.* (2024), in which the tensile strength of flax/PLA composites increased from 160 to 170°C. Further increase in temperature up to 180°C results in decreased tensile strength.

The tensile strength is the lowest at a short mixing time and lower mixing temperature. This condition is relatively poor, which might be attributed to the mixing time being too short. When the time was too short, the dispersion of fibres was not sufficient,

and/or an inconsistent melt of the PLA polymer would occur. Therefore, this might lead to poor stress transfer due to the poor interfacial adhesion between the KDC and matrix. A similar trend was observed in a study by Tharazi *et al.* (2017a). The study reported that the tensile strength of unidirectional long kenaf fibre-reinforced PLA composite increased with increasing mixing time from 5 to around 8 min. Increasing the mixing time beyond 8 min results in decreased tensile strength. From Figure 3(a), the processing parameter of 170°C and 20 min seems to be the best condition for mixing 5% KDC/PLA composite since the optimum tensile strength was reached. Initially, this parameter can be used to proceed with the mixing of higher loadings of KDC composites. However, the second response that needs to be taken into consideration is the stock temperature or maximum temperature of blends during the mixing of the composite (Figure 4). This stock temperature is an important indicator in mixing the composite, and typically, the target value is below 200°C to avoid fibre degradation.



(a) (b)

Figure 3. Contour plots representing the effects of reaction temperature and time on (a) tensile strength and (b) stock temperature.

3.3. Stock Temperature

Figure 3(b) presents the effects of processing temperature and time on the stock temperature of 5% KDC/PLA composite. It was found that the increases in processing temperature significantly affected the stock temperature, resulting in a higher stock temperature . However, this result demonstrated that the processing time did not significantly influence the stock temperature. This result is in agreement with the regression

coefficient analysis, where the mixing temperature term was significant in the stock temperature model. From the plot, it was observed that when the mixing temperature was increased, the stock temperature also increased. The contour areas represent constant stock temperatures at 189, 192, 195, 198, and 201ºC. The contour at higher temperatures shows a higher stock temperature (> 200ºC). Therefore, a stock temperature below 200ºC was required to ensure that the fibre would not easily degrade. It has been reported by Herrmann *et al.* (1998) that reduction of fibre strength has been shown to occur at temperatures as low as 150ºC and 200ºC, with strength reduced by 10% in 10 min. Moreover, most natural fibres have low degradation temperatures (~ 200°C) (Sgriccia *et al.*, 2008). Meanwhile, as the mixing time was increased, a constant stock temperature was attained at a specific mixing temperature. This phenomenon arose because the measured stock temperature was obtained at one peak point (the maximum stock temperature) based on the mixing torque-temperature curves. This is in agreement with research by Patti *et al.* (2020) , in which the stock temperature reaches a constant value at a specific mixing temperature of 190°C after 15 min.

When the processing temperature is fixed at a certain temperature, the original temperature of the blends will be higher for a certain period. Figure 4 shows an example of the torque-temperature curve of the KDC/PLA composite. From this figure, the processing temperature was fixed at 170ºC, and after a while, the temperature started to drop when the polymer resin was poured into the chamber. Later, the polymer started to melt, and the temperature was increased. It was then increased dramatically after adding the KDC. Finally, the temperature reached a constant temperature parallel to the stabilisation zone of the blends. This condition might have been generated by significant interparticle friction, which caused overheating in the mixing chamber during the blending of PLA and fibre (Hidalgo *et al.*, 2012). It could also be due to the work done by the screw that transferred the fraction energy (interaction between the blend and screw due to shear force) to heat energy based on the conservation of energy theory. This phenomenon can also be observed from the results in Table 2. It was observed that the recorded stock temperature reached values higher than the set mixing temperature, with a negligible effect of increasing the processing time. For mixing temperatures of 160, 170, and 180°C, the stock temperature reaches approximately 188, 196, and 203°C, respectively, with the increment ranging from 23 to 28°C. Patti *et al.* (2020) reported a similar pattern in which the blending of PLA and fibre at 170 and 190°C achieved stock temperatures of 187 and 200°C, with a maximum improvement of approximately 20°C. During the melting of the PLA matrix, self-heating

effects occur due to friction between cellulose fibres, PLA granules, or the walls of the mixer. This friction results in a significant difference between the actual temperature of the compounds and the temperature within the mixing chamber.

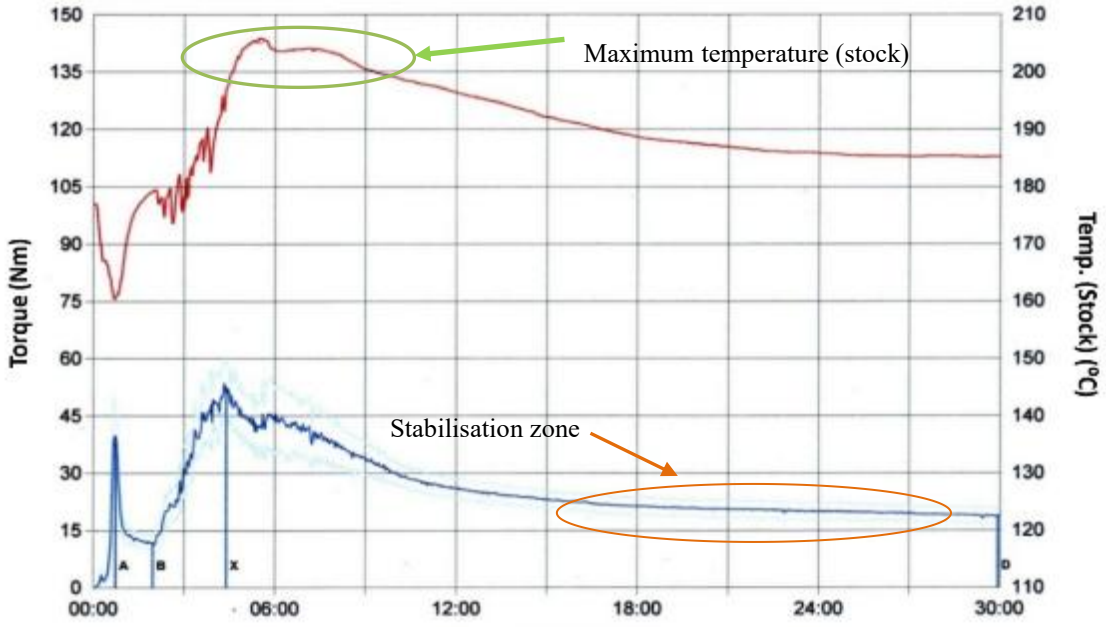


Figure 4. Example of torque versus time curve and temperature (stock) versus time curve of KDC/PLA composite in Brabender twin-screw mixer.

3.4. Optimisation

Later, both the contour plots of tensile strength and stock temperature responses were overlaid, and the optimum condition was measured. The responses were targeted at a certain range of values. The region that has been produced represents the suggested condition where the overlaid area consists of the studied responses (Figure 5). The target values for tensile strength and stock temperature were 59 to 61 MPa and 188 to 200ºC, respectively. Since the tensile strength of neat PLA is 59 MPa (based on the measurement in ASTM 188L), the minimum target value for tensile strength in this overlay was 59 MPa and goes up to the maximum tensile strength of 63 MPa. Meanwhile, the stock temperature was set at a temperature below 200ºC to avoid fibre degradation. Thus, from this overlaid plot, there are two possibilities for choosing the best conditions for mixing KDC and PLA polymer, which are 170ºC for 20 min and 170ºC for 30 min. However, good homogeneity of the composite (the distribution of fibre within the polymer matrix during mixing) was also the main concern in the current study. Based on the preliminary study, sufficient processing duration is important since the stabilisation zone indicates that the composites are well-mixed and equally distributed within their matrix. Indeed, this stabilisation zone

could not be performed via RSM due to the measured data being obtained by monitoring the trend of the mixing torque curve (Figure 4).

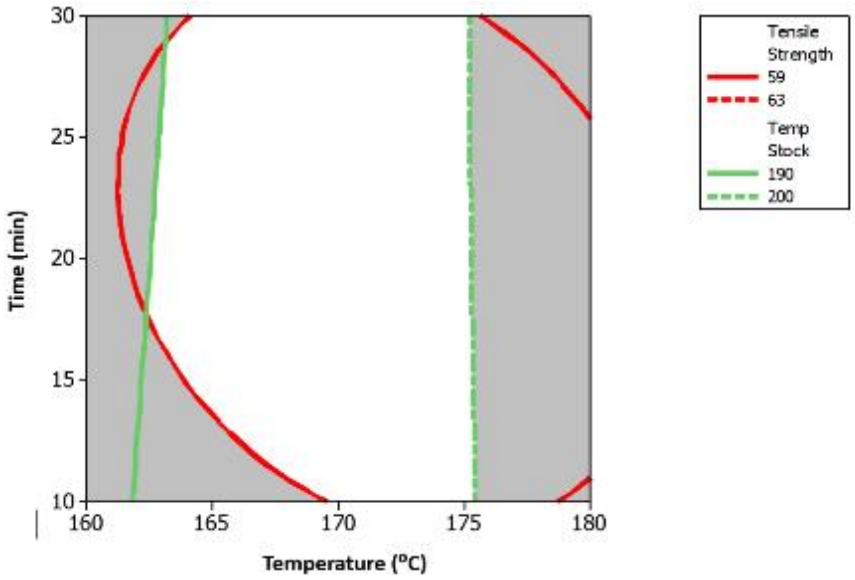


Figure 5. Overlay of tensile strength and stock temperature response.

Figure 6 shows the mixing torque curves of KDC/PLA composites produced at cellulose loadings ranging from 0–60% KDC. At higher KDC loadings, the torque curves show that a longer time is required to gradually mix the cellulose into the mixer until it reaches a constant torque value towards the end of the processing time. Overall, increasing the cellulose loading increases the final value of the stabilisation zone. Macedo *et al.* (2020) reported that the fibres and polyethylene matrix have been completely blended by observing the steady-state values of torque at the end of the process. The curves of the mixing torque properties have also been similarly observed by Patti *et al.* (2020). For these reasons, the best processing condition for producing KDC/PLA composite at higher KDC loading was 170°C for 30 min to achieve a better stabilisation zone during composite compounding.

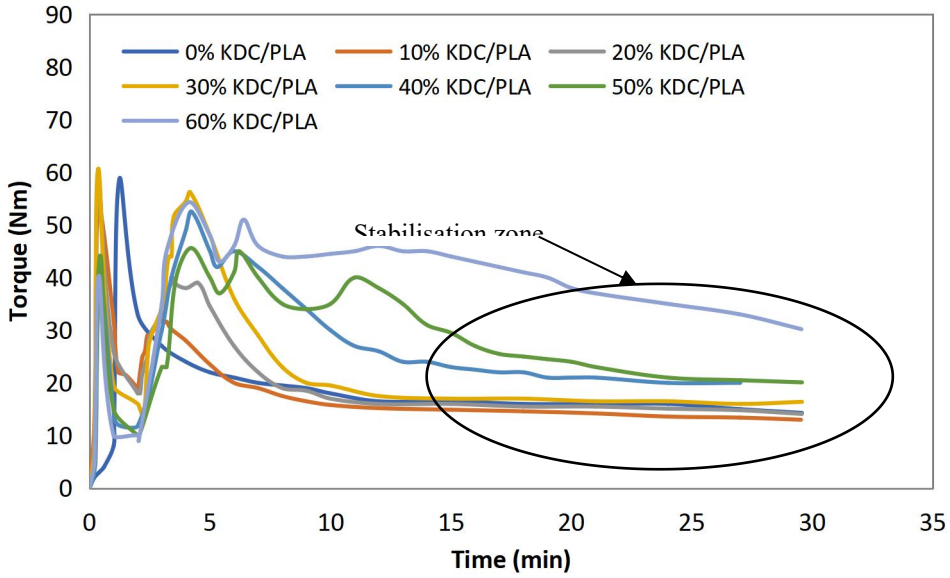


Figure 6. Torque versus time curves of KDC/PLA composite at various KDC loadings.

4. Conclusions

This study successfully optimised the melt mixing parameters for KDC/PLA composites using RSM. The results indicated that both the mixing temperature and time significantly affected the tensile strength and stock temperature of KDC/PLA composites. Specifically, the mixing temperature showed strong statistical significance ($P < 0.0500$) for both responses. Increasing the temperature from 170 to 175°C and the processing time from 15 to 25 min increased tensile strength to the maximum. Increasing the temperature from 160 to 180°C also significantly increased the stock temperature, but the processing time had a minimal effect. The optimal conditions for the 5% KDC/PLA composites were found to be 170°C and 30 min, which maximised tensile strength while keeping the stock temperature below 200°C to prevent fibre degradation. Overall, the findings of this research showed that RSM is an effective tool for determining the optimum process parameters to achieve the desired properties. Optimising the melt mixer parameters not only improves the mechanical properties of the composites but also preserves the thermal stability of natural fibres. The sample size can also be minimised to save time and raw materials by measuring the best process performance. Furthermore, these findings show the potential of 5% KDC/PLA biocomposites as promising materials for food packaging applications where mechanical strength is important. This study has significant implications for the development of sustainable, environmentally friendly, and high-performance biocomposites that can be used in various industries, including packaging materials and other consumer goods. Future research could incorporate additional mechanical tests, including flexural and

impact resistance, alongside thermal analysis, which provides a better and deeper understanding of the material's performance.

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