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Materials Selection of Thermoplastic Matrices for 'Green' Natural Fibre Composites for Automotive Anti-Roll Bar with Particular Emphasis on the Environment

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In this study, selection of thermoplastic polymers to be used in natural fibre-reinforced polymer composite is performed using Quality Function Deployment for Environment technique. The candidate materials for the matrix in composites are thermoplastic polyurethane, high-density polyethylene, low-density polyethylene, polystyrene and polypropylene and the selection process is carried out based on the design requirements of an automotive anti-roll bar. Requirements are collected through a study on the voice of customers and the voice of the environment. The approach is followed by sensitivity analysis using Expert Choice software based on the Analytic Hierarchy Process method. From the analysis, high-density polyethylene scored the highest (28.76%), and followed by thermoplastic polyurethane, which had 22.30% of the overall score. Finally, Young's modulus of hemp fibre reinforced high-density polyethylene and thermoplastic polyurethane composites were compared, predicted using the Halpin-Tsai method. The results show that hemp-reinforced thermoplastic polyurethane composite shows higher Young's modulus of 10.6 GPa, compared with hemp-reinforced high-density polyethylene composite (8.27 GPa). Based on these two analyses, thermoplastic polyurethane is selected as the most suitable polymer matrix for natural fibre composites for automotive anti-roll bar.

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NOMENCLATURE

QFDE = Quality Function Deployment for Environment
AHP = Analytic Hierarchy Process
VOC = Voice of Customer
VOE = Voice of Environment
HOQ = House of Quality
RS = Raw Score
RW = Relative Weight
NRS = Normalised Raw Score
TUSL = Technical Upper Specification Limit
TRT = Technical Requirement Targets
W = Weight
E_m = Modulus of Matrix
ξ = Shape Fitting Parameter
V_f = Fibre Volume Fraction
E_f = Modulus of Fibre

1. Introduction

Up to date, attempt to produce anti-roll bar from synthetic composites (to replace steel) was made, but there is still no attempt to introduce natural fibre composites for similar structural application. Natural fibre composites have been used in many different industries such as in automotive, aerospace, construction, furniture and marine industries. They are known to be suitable alternative materials especially for eco-friendly products.[1] The advantages of having natural fibre composite as the main material in product development including lightweight, low cost, has low energy consumption, recyclable, has high stiffness properties, and is biodegradable and non-abrasive.[2] Due to all these advantages, many researchers have studied a variety of natural fibres that could be used to reinforce the polymer composite. As the matrices in natural fibre composite, polymer materials could improve the properties of the natural fibres and open up more opportunities for the natural fibres to be applied in various areas.[3] Thermoplastic is one of the available options for matrix commonly found in natural fibre polymer-reinforced composites. In comparison with thermoset polymer, the advantages of having thermoplastic as the matrix in the composite are lower processing cost, better flexibility and that it is easy to mould into complex components, and also it exhibits better mechanical properties as a composite.[4] Furthermore, due to environmental concerns, thermoplastic based composite is increasingly drawing attention of many researchers due to its ability in recycling and incineration.[5] Polyethylene (PE), polypropylene (PP), thermoplastic polyurethane (TPU) and polystyrene (PS) are examples of thermoplastic polymers that have been used as matrices for natural fibre to form composites.[6]

Thermoplastic composite is a material that offers tremendous opportunities regarding its role as an alternative material in industries such as automotive, construction, and aerospace. Applications of thermoplastic composite in product development have been widely studied by numerous scholars from different backgrounds and cultures, from the study of the material characterisations in material science to the manufacturing process of thermoplastic composite-based products; and several other research areas have been explored in between. These include the material selection process and design process of the development of thermoplastic composite-based products. In composite material design, it is necessary to link the design steps with the overall design constraints through similar control parameters that would lead to a parallel approach to save time and cost in product design development.[7] Up until now, researchers have proposed new techniques for materials selection based on the available and attainable information. Selecting a suitable material from a range of metal-based materials is less challenging than selecting one from a group of composite-based materials because of the readily available information about the former group's properties. However, for composite-based materials, some uncertain and vague properties' information has to be used if no other options are available. Some new approaches have been proposed by researchers as solutions for past material selection techniques that were not systematic and subjective. For example, Mayyas et al.[8] proposed a material selection approach that could deal with subjective judgement from a sustainability perspective. In addition, environmental impact of the product design should be included in material selection to address sustainability awareness.

Furthermore, Mayyas et al.[9] also employed Quality Function Deployment (QFD) in selecting appropriate materials for the automotive body-in-white panels. Metal-based materials dominated the selection as they gained higher score in the evaluation. However, the automotive components included in the body-in-white would bear less extreme mechanical loading compared to the other automotive components, such as torsion bar or anti-roll bar. Thus, automotive bar components require more attention from a technical perspective. Moreover, QFD is reported to be highly vague and inconsistent due to the involvement of human-based decisions that provide the data for the QFD.[10] Substitution of materials – moving from metal-based to composite-based materials – would require an effective approach to avoid incorrect decisions that could cause terrible damage in the future. Regarding this, Al-Oqla et al.[11] presented a proper decision making models that utilized Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for natural fibre composites to evaluate the potential reinforcement conditions with regards to mechanical properties. On the other hand, Giudice et al.[12] proposed an approach that integrated mechanical and environmental performance. However, the approach requires designers to have strong background knowledge on the environment. A less complicated and direct approach is required as both mechanical and environment aspects are considered simultaneously in selecting materials. Environmental concern at an early stage of design process is very important to support the initiative to move towards green or environmentally friendly product. Therefore, in conceptual design, material selection is suggested by Sapuan et al.[13] to be performed at the beginning of the process and it is suitable to implement the environmental aspect for the green design and sustainability factor. On the other hand, Lee and Badrul[14] have proposed a framework that based on axiomatic design principles for the End-of-Life management, green supply chain and sustainable manufacturing. Besides that, Qiang et al.[15] suggested in developing conceptual design in a perspective of the whole life cycle and modular design to support the product green design. Hence, a lot of approaches have been proposed for the green design and with regards of the importance of material selection in conceptual design process, environmental concerns should be applied initially as in material selection process.

In this study, selection of a thermoplastic matrix for the natural fibre composite is carried out for an automotive anti-roll bar. A systematic and simple approach is required for this purpose. Based on total design method by Pugh,[16] as market investigation included during initial stage of product design development, the selection process is performed in consideration of customer requirements or known as Voice of Customers (VOC) and Voice of Environment (VOE). Quality Function Deployment for the Environment (QFDE) is used to select the suitable thermoplastic matrix and the results are verified by sensitivity analysis from Expert Choice software based on the Analytic Hierarchy Process (AHP) method. In the final stage, two materials with the highest scores are compared based on their properties as predicted from the Halpin-Tsai model. The matrix that exhibits better properties is selected as the suitable matrix for reinforcement in natural fibre composites.

2. Methodology

In this study, an approach is proposed according to the general procedure of material selection with a new multi-criteria decision-making (MCDM) technique; which is using QFDE. QFDE is an extended version of QFD which includes the environmental aspects in material selection simultaneously and is understandable for designers who do not have not strong knowledge of environmental science. Moreover, anti-roll bar is a structural component, with specific design requirements in term of function, environment and cost. Therefore, MCDM for materials selection process is performed to analyse the performance of the pool of candidate materials and their attributes with multi-requirements involved simultaneously, to rank the best material for the application.

The construction of QFDE in this study is different from the conventional practice, as only three phases are included in the process: Phase I is for the House of Quality (HOQ), Phase II is for material characteristics deployment and Phase III is for the material selection matrix. This three-phase QFDE is detailed in Fig. 1. In Phase I, HOQ is employed where the VOC and VOE are translated into technical requirements. The relationship between VOC and VOE with technical requirements is evaluated as either strong, medium or weak. A material characteristics deployment matrix is developed in Phase II in order to meet customer-based technical requirements with material constraints. Finally, in the third phase, a list of potential materials is evaluated based on the material constraints scores, which are correlated with customer requirements. VOC could be obtained through literature studies, questionnaires, interviews and surveys which is based on stakeholders, end users and manufacturers' requirements, while VOE, which is based on environment requirements could be obtained as listed in Masui's[17] study as follows: (1) Less material usage, (2) Easy to transport and retain, (3) Easy to process and assemble, (4) Less energy consumption, (5) High durability, (6) Easy to reuse, (7) Easy to dissemble, (8) Easy to clean, (9) Easy to smash, (10) Easy to sort, (11) Safe to incinerate, (12) Safe to go into landfill, (13) Harmless to living environment, (14) Safe emission and (15) Easy to dispose of.

Particularly, the HOQ in Phase I is constructed as a template, as shown in Fig. 2. Details of the HOQ are explained as follows:

(1) Room 1 is filled with a list of customer and environmental requirements.

(2) Room 2 is filled with the weightage for each customer and environmental requirement.

(3) Room 3 is filled with the technical requirements translated from VOC and VOE.

(4) Room 4 is filled with the direction of improvement (DI), which indicates whether the particular technical requirements should be improved or reduced.

(5) Room 5 is filled with the relationship between customer and environmental requirements and technical requirements. Scores of 1, 3, and 9 were used to define the relationship – either weak, medium or strong respectively.

(6) Room 6 is filled with the interrelationship between technical requirements according to score 1 or 2. Score 1 is given to the relationship that denotes that improvement in meeting one of the specifications may worsen the other, and score 2 is given to the relationship that denotes improvement in meeting one of the specifications will also improve the other.

(7) Room 7 is filled with the scores from Rooms 5 and 6. The results will be raw score (RS), relative weight (RW), normalised raw score (NRS), technical upper specification limit (TUSL), technical requirement targets (TRT), weight (W) and technical rank based on the weightage.

Particularly in Room 7, the RSs are calculated as the sum of the product of Room 2 (R2) by the scores assigned for every technical requirement in the same row as in Room 5 (R5) as in Eq. (1). Next, NRS is performed by dividing every RS by the maximum score in that row as in Eq. (2). In order to reflect an outcome of the relationship between customer requirements in Room 1 and the technical requirements in Room 3, TUSL is calculated as the sum of the technical requirements interrelation scores in Room 6 in the same column diagonally. Then, the TRT is calculated by multiplication of NRS and TUSL to prioritise all technical requirements as in Eq. (3). Lastly, W is calculated by dividing every score in TRT by the summation score of TRT as in Eq. (4). The higher the value of W, the more important the technical requirements and that is the way they are ranked.

$$RS = \sum_{i,j=1}^{5} (R2_i \times R5_{ij}) \tag{1}$$

$$NRS = RS/RS_{max} \tag{2}$$

$$TRT = NRS \times TUSL \tag{3}$$

$$W = TRT/\sum TRT \tag{4}$$

In the second phase, a similar template is used without Room 6. Direction of improvement is only considered once in this study, during selection of materials in Phase III. After the score for each material constraint is obtained from Phase II, selection of materials is performed in Phase III. Simultaneously, evaluation of potential materials is performed in Expert Choice software, which takes advantage of the concept of Analytic Hierarchy Process (AHP) is used in making a decision. The hierarchy framework for AHP is built based on the criteria from QFDE-Phase III. The evaluation is carried out on a

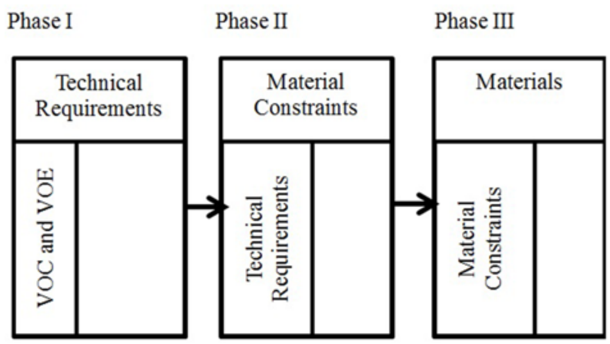


Fig. 1 Three-Phase quality function deployment for environment

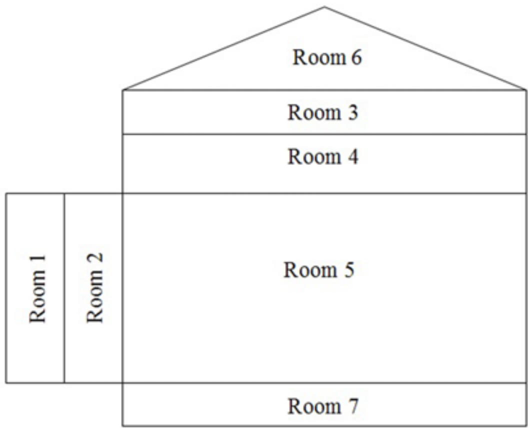


Fig. 2 Construction of house of quality

pairwise basis comparison and the score for each criterion should be near the results from QFDE. Sensitivity analysis is performed to verify the earlier evaluation using Expert Choice software. Finally, two thermoplastic matrices that have the best two highest scores are evaluated based on Young's modulus of the composites using the prediction model from the Halpin-Tsai method. The Halpin-Tsai method is presented as follows:

$$E = E_m\left(\frac{1+\xi\eta V_f}{1-\eta V_f}\right) \tag{5}$$

where the parameter

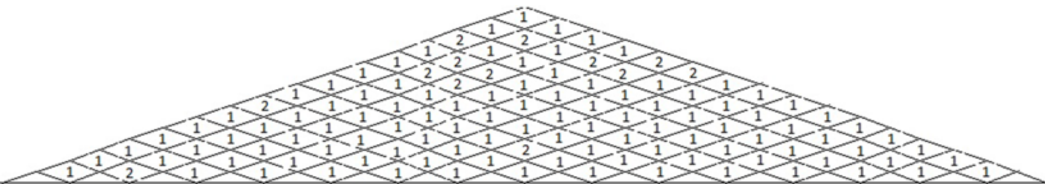
$$\eta = \left(\frac{(E_f/E_m)-1}{(E_f/E_m)+\xi}\right) \tag{6}$$

Here, E_m, ξ, V_f and E_f are modulus of matrix, shape-fitting parameter (hemp = 8), fibre volume fraction and modulus of fibre.[18]

3. Results and Discussion

The automotive anti-roll bar is the component that links the wheels and reduces the amount of body roll during cornering or uneven road conditions (See Fig. 3). As mentioned in studies by past researchers[19-25] the design of an automotive anti-roll bar must be extremely robust as the component often has to bear extreme mechanical loading. The elastic modulus of the materials should be high in order to resist bending and torsional loading.[23] Most automotive components are designed with lightweight materials in order to reduce curb weight of the vehicle. Currently, lower-weight vehicles are in high demand because they consume less fuel compared to heavier vehicles.[26] Therefore, the anti-roll bar design has to consider non-heavy materials in order to reduce the vehicle's curb weight. Moreover, one of the design requirements mentioned by experts is high fatigue strength as, when the anti-roll bar encounters multiple loadings, this could cause crack initiation leading to design failure. Number of cycles before it fails must be high in order to extend the ARB's lifetime.[24,27,2] Furthermore, the anti-roll bar design needs impact and break resistance, especially in high vibration conditions. All these customer requirements are included in the HOQ together with the environment requirements as listed by Masui[17]. In summary, the development of a composite anti-roll bar requires the following criteria: (1) Price, (2) Easy to reuse, (3) Easy to recycle, (4) Less transportation, (5) Easy to manufacture, (6) Durable, (7) Lightweight, (8) Easy to maintain, (9) Reliable, (10) Long lifetime,

Fig. 3 Automotive anti-roll bar and its components



		Density	Tensile Strength	Lifetime	Young's modulus	Shear Modulus	Elongation at break	Toxicity of materials	Transportation	Waste End-of-Life	Emissions in use	Maintenance	Rate of reusability	Rate of recyclability	Price	Safety factor	Machinability
Unit		kg/m3	m3	hr	MPa	N/mm	%	n/a	km	n/a	n/a	n/a	%	%	RM	n/a	n/a
Direction of improvement		-1	1	1	1	1	1	-1	-1	-1	-1	-1	1	1	-1	1	1
Characteristics	w																
Price	3.80%	3							3			1	1	1	9		3
Easy to reuse	8.70%			3								1	9				
Easy to recycle	6.80%			1				1		3				9			
Less transportation	5.30%								9								
Easy to manufacture	2.50%		1					1									9
Durability	15.90%	1	9	3	9	9	1					1				3	
Lightweight	8.90%	9	3						1						3		
Easy to maintain	8.30%			3								9					
Reliability	9.00%			3								9	1	1			
Long lifetime	7.40%			9								1	3				
Endure impact	5.70%				9	9	9									3	
Not easy to break	5.10%				9	9	3									9	
Free from hazardous substance	7.10%	1						9		3	9			3			
Fewer materials	1.90%	3	3							1				1	9		1
Environmental safety	3.50%							9	3	9	9		1	1			
	RS	120.20	178.00	199.10	240.30	240.30	82.50	104.70	78.50	75.10	95.40	191.50	116.80	100.70	78.00	110.70	35.80
	RW	0.0587	0.0869	0.0972	0.1174	0.1174	0.0403	0.0511	0.0383	0.0367	0.0466	0.0935	0.0570	0.0492	0.0381	0.0541	0.0175
	NRS	0.5002	0.7407	0.8285	1.0000	1.0000	0.3433	0.4357	0.3267	0.3125	0.3970	0.7969	0.4861	0.4191	0.3246	0.4607	0.1490
	TUSL	17.0000	19.0000	18.0000	16.0000	17.0000	16.0000	16.0000	16.0000	15.0000	16.0000	15.0000	17.0000	17.0000	16.0000	18.0000	17.0000
	TRT	8.5035	14.0741	14.9139	16.0000	17.0000	5.4931	6.9713	5.2268	4.6879	6.3521	11.9538	8.2630	7.1240	5.1935	8.2921	2.5327
	W	0.0596	0.0987	0.1046	0.1122	0.1192	0.0385	0.0489	0.0367	0.0329	0.0446	0.0838	0.0580	0.0500	0.0364	0.0582	0.0178

Fig. 4 Phase I of quality function deployment for environment-house of quality: customers and environmental voices vs. technical requirement

(11) Impact resistance, (12) Not easy to break, (13) Free from hazardous substance, (14) Less material usage and (15) Environmentally safe. Criteria (1), (7)-(12) are from VOC and criteria (2)-(6), (13)-(15) are from VOE.

In the first phase, the customer and environmental requirements in Room 1 are weighted using the AHP, as the priority vector of each requirement gained from AHP are later filled in Room 2 of HOQ, as shown in Fig. 4. VOC obtained higher score which is 64.2% from the overall score of requirements while VOE obtained 35.8%. The related technical requirements are filled in Room 3 with the direction improvement in Room 4 for further reference. The relationship between the customer and environmental requirements and technical requirements is evaluated in Room 5. Later, the correlation between each of the technical requirements is evaluated in Room 6. Finally, all the scores are calculated in Room 7 to determine the weight of all the technical requirements that would be useful in Phase II. Here, the results show that the design of the anti-roll bar requires high durability and reliability, where the Young's modulus, shear modulus and the lifetime of the anti-roll bar should be high, as they scored 11.22%, 11.92% and 10.46% respectively.

In the second phase, the weighted technical requirements are placed at the left side of the matrix and the related material constraints are filled in at the top of the matrix, as shown in Table 1. Similar to Phase I, the relationship between the technical requirements and material constraints is evaluated and the total score is calculated and presented at the bottom of the matrix. This relationship would imply that the proposed material selection approach is driven by the customers and environment from the beginning of the process. Since the technical requirements are correlated with the customer and environmental requirements at Phase I, the criteria for the material selections are based on customer and environmental expectations. Therefore, as presented in Table 1, the most important criteria in selecting the suitable thermoplastic matrix for the natural fibre composite anti-roll bar are the high value of fracture toughness, elongation at break and Young's modulus, as they scored 18.29%, 15.95% and 10.19% of the overall score respectively.

Finally, in Phase III, material selection is performed taking into consideration the material constraints driven by customer and environmental requirements since Phase I. At this time, the weighted material constraints from Phase II are placed at the left side of the matrix and the material candidates are placed at the top of the matrix. Material candidates for this selection consist of the five common thermoplastic matrices, which are high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polyurethane (TPU) and polystyrene (PS). Similarly, all the material properties of the candidate materials are evaluated for each material constraint respectively. The evaluation of the materials' selection is based on the normalised value of the material properties, as shown in Table 2. The results from the total scores are presented in Table 3. As can be seen in Table 3, HDPE gained the highest score with 28.76% while TPU is positioned in the second rank with 22.30%. LDPE gained 20.32% and so is placed in the third rank.

Next, sensitivity analysis is carried out by using Expert Choice software based on AHP. The hierarchy framework for the AHP is built based on the criteria from QFDE-Phase III. The evaluation is carried out on a pairwise basis comparison and the score for each criterion is similar to the result from QFDE. Fig. 5 shows the hierarchy framework of the thermoplastic selection with the score for each criterion. Later,

Table 1 Phase II of quality function deployment for environment-material characteristics' deployment: technical requirements vs. material constraints

Technical measurement	Weight	Density	Young's modulus	Fracture toughness	Elongation	Tensile strength	Impact strength	Chemical resistance	Weather resistance	Water absorption	CO2 footprint	Raw cost	Thermal conductivity
Density	5.96%	9					1						
Tensile strength	9.87%					9							
Lifetime	10.46%			9	9		3			1			
Young's modulus	11.22%		9				3						
Shear modulus	11.92%			1	3								
Elongation at break	3.85%				9	3							
Toxicity of materials	4.89%							9					
Transportation	3.67%	3											
Waste end of life	3.29%								9	3			3
Emissions in use	4.46%							1		9	9		3
Maintenance	8.38%								3	1			
Rate of reusability	5.80%			3					3	1			
Rate of recyclability	5.00%			3					3	1			
Price	3.64%											9	
Safety factor	5.82%			9			1						
Machinability	1.78%		3		1	3					9		3
	RS	64.67	106.32	190.78	166.36	105.72	76.82	48.46	87.12	79.59	56.08	32.78	28.56
	RW	0.0620	0.1019	0.1829	0.1595	0.1013	0.0736	0.0464	0.0835	0.0763	0.0538	0.0314	0.0274

the candidate materials are evaluated and ranked based on the score that they gained from the AHP. As expected, the results are very close to the QFDE's result, where HDPE scored 0.257, followed by TPU (0.217) and LDPE (0.203), as shown in Fig. 6. Next, the sensitivity analysis is performed by increasing each of the criteria by 20%. Table 4 shows the results from the sensitivity analysis. High-density polyethylene maintained its position as it scored the highest in the analysis in four cases. This provides strong agreement that the decision is stable and insensitive to small changes in factors' weight.[29]

From the results, QFDE concluded that HDPE is the most suitable polymer matrix for the natural fibre composite because it gained the highest score in the evaluation. High-density polyethylene has been found to perform well as reinforced matrix in many studies in natural

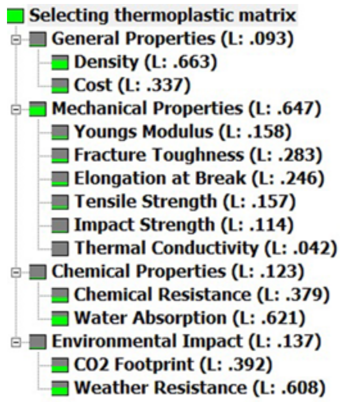


Fig. 5 Hierarchy framework for selecting thermoplastic matrix

Table 2 Properties of thermoplastic matrices for natural fibre composites material selections[30]

Properties	Unit	PP	PS	HDPE	LDPE	TPU
Density	g/cm^3	0.899-0.920	1.04-1.06	0.94-0.96	0.910-0.925	1.12-1.24
Young's modulus	GPa	0.95-1.77	4-5	0.4-1.5	0.055-0.38	1.31-2.07
Fracture toughness	MPa.m$^{0.5}$	2.3-2.42	0.7-1.1	1.52-1.82	1.21-3.39	1.84-4.97
Thermal conductivity	W/m/K	0.24	0.15	0.63	0.33	0.235-0.244
Elongation	%	43-73.2	1.2-2.5	1120-1290	100-650	60-550
Tensile strength	MPa	26-41.4	25-69	14.5-38	40-78	31-62
Impact strength	J/m	21.4-267	1.1	26.7-1068	>854	9.42-39
Chemical resistance	n/a	0.76	0.48	0.76	0.76	0.4
Water absorption (@24 hours)	%	0.01-0.02	0.03-0.10	0.01-0.2	<0.015	0.15-0.19
Cost	USD/kg	2.14-2.36	2.14-2.35	1.76-1.94	1.78-1.98	5.55-6.11
CO_2 footprint	kg/kg	1.89-2.08	1.05-1.17	0.897-0.991	3.29-3.64	3.52-3.89

Table 3 Phase III of quality function deployment for environment-material selection: material constraints vs. thermoplastic matrix

Material constraints	DI*	Weight	PP	PS	HDPE	LDPE	TPU
Density	-1	6.20%	0.74	0.85	0.77	0.75	1.00
Young's modulus	1	10.19%	0.35	1.00	0.30	0.08	0.41
Fracture toughness	1	18.29%	0.49	0.22	0.37	0.68	1.00
Elongation	1	15.95%	0.06	0.00	1.00	0.50	0.43
Tensile strength	1	10.13%	0.53	0.88	0.49	1.00	0.79
Impact strength	1	7.36%	0.25	0.00	1.00	0.80	0.04
Chemical resistance	1	4.64%	1.00	0.56	1.00	1.00	0.53
Weather resistance	1	8.35%	0.60	1.00	1.00	0.60	1.00
Water absorption	1	7.63%	0.10	0.50	1.00	0.08	0.95
CO2 footprint	-1	5.38%	0.53	0.30	0.25	0.94	1.00
Raw cost	-1	3.14%	0.39	0.38	0.32	0.32	1.00
Thermal conductivity	1	2.74%	0.38	0.24	1.00	0.52	0.39
Recycle	1	#N/A	1.00	1.00	1.00	1.00	1.00
		RS	23.41	30.51	54.20	38.29	42.01
		RW	12.42%	16.19%	28.76%	20.32%	22.30%
		Rank	5	4	1	3	2

*DI- Direction of Improvement

Table 4 Rank of alternative priorities obtained by simulating three scenarios of sensitivity analysis for different main criteria with respect to goal

Rank	General properties		Mechanical properties		Chemical properties		Environmental impact	
	Increased by 20%		Increased by 20%		Increased by 20%		Increased by 20%	
	Alternatives	W (%)	Alternatives	W (%)	Alternatives	W (%)	Alternatives	W (%)
1	HDPE	24.3	HDPE	24.6	HDPE	26.7	HDPE	26.0
2	LDPE	21.2	LDPE	22.6	TPU	22.4	TPU	21.1
3	TPU	18.6	TPU	21.4	LDPE	18.7	LDPE	18.5
4	PS	18.4	PS	16.3	PS	17.7	PS	19.5
5	PP	17.4	PP	15.1	PP	14.5	PP	14.8

fibre composites such as curaua, oil palm, sisal, rice husk, wood, hemp, coir, and bamboo.[31–35] In comparison with the LDPE composite, the HDPE composite exhibits higher tensile strength, according to the statistical analysis, by 21.2%.[36]

Thermoplastic polyurethane, which was ranked in second place, could also be considered as a suitable polymer matrix for the natural fibre composite. Comparison between HDPE and TPU is made based on Young's modulus value for both composites. Facca et al.[37] in their study found that Rule of Mixture (ROM) could adequately predict the value of the tensile properties of natural fibre-reinforced thermoplastic composites. However, Ku et al.[36] in their study agreed that the Halpin-Tsai model exhibited predicted results that agreed well with experimental results for Young's modulus of natural fibre-reinforced polymer composites. Therefore, comparison between prediction value of Young's modulus of natural fibre-reinforced HDPE composite and thermoplastic polyurethane composite was performed using Halpin-Tsai, as also suggested by Mansor et al.[38]

In the current work, Young's modulus of hemp fibres reinforced with HDPE is taken as a case study. As presented in Fig. 7, the predicted value of Young's modulus of hemp/HDPE composite is similar to the value presented in Facca et al.'s[18] study and it was almost identical to the value from the experimental method.

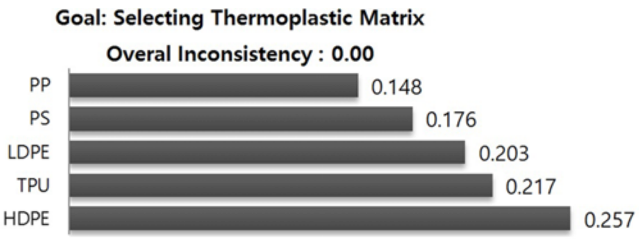


Fig. 6 Result of thermoplastic matrix selection with respect to goal

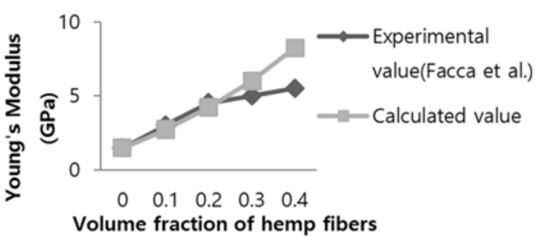


Fig. 7 Comparison of Young's modulus for the experimental value and the calculated value of hemp-reinforced high-density polyethylene composite[18]

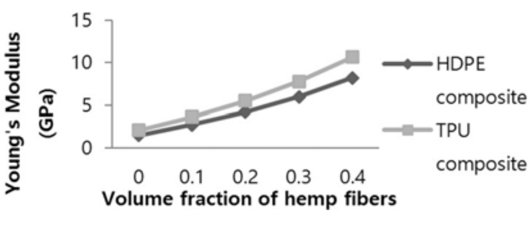


Fig. 8 Comparison of Young's modulus for the high-density polyethylene composite and the thermoplastic polyurethane composite

Therefore, this study extends the comparison between HDPE and thermoplastic polyurethane. The predicted values for Young's modulus of hemp/HDPE composite and hemp/TPU composite are presented in Fig. 8. As per the results, natural fibre-reinforced TPU composite exhibits a higher value compared to the natural fibre-reinforced HDPE composite. Thus, the higher value could imply that the former has better properties and so TPU could be selected as the best polymer matrix for the natural fibre composites.

Thermoplastic polyurethane could be found as a reinforcement agent in natural fibre composites. El-Shekeil et al.[39] conducted a study on a composite of thermoplastic polyurethane reinforced with short kenaf fibre. Sharma and Kumar[40] conducted a study on a banana fibre-reinforced thermoplastic polyurethane composite where the composite showed optimum mechanical properties. Polyurethanes represent an important class of thermoplastic polymers as their mechanical, thermal, and chemical properties can be tailored by the reaction of various polyols and polyisocyanates.[41] The properties of this class of polymer can be easily engineered to their application environments.[42] Thermoplastic polyurethanes can also be found in synthetic fibre reinforced composites such as short glass and carbon fibres as polymer matrix that improves the mechanical performances and thermal stability of the composites.[43,44]

4. Conclusions

In summary, material selection of a thermoplastic matrix for natural fibre composite anti-roll bar was carried out using QFDE that is driven by the voices of customers and the environment. The three-phase QFDE method has exhibited results that show HDPE is the most suitable matrix as a reinforced agent in natural fibre composite. The result ranked HDPE (28.76%) in first place, followed by TPU (22.30%), LDPE (20.32%), PS (16.19%) and PP (12.42%). Furthermore, the sensitivity analysis verified the results by showing HDPE's unchanged position in the first rank in four different cases. The sensitivity analysis was carried out by increasing the weight of four selection criteria - general properties, mechanical properties, chemical properties and environmental impact - by 20%. In the final evaluation, Young's modulus of the HDPE and TPU composites was predicted using the Halpin-Tsai method. Comparison analysis showed that the natural fibre-reinforced TPU composite has a higher value of Young's modulus, which was 10.6 GPa at 40% of fibre volume fraction, than the natural fibre-reinforced HDPE composite, which was only 8.27 GPa. This would finalise the selection by demonstrating that TPU is the most suitable matrix to be used as a reinforcing agent for natural fibre composites, particularly in automotive components. Moreover, TPU satisfies the requirements on mechanical properties as desired by customers and environment for design of automotive anti-roll bar. On the other hand, this study has shown that QFDE assists engineers in selecting materials easily where a simple approach is required that is driven by customers and the environment. This approach also exhibits better understanding of the environmental perspective in material selection, which is applicable for any type of material. In future, the properties of the natural fibre-reinforced TPU composite should be evaluated based on mathematical modelling.

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