Combined Multi-criteria Evaluation Stage Technique as an Agro Waste Evaluation Indicator for Polymeric Composites: Date Palm Fibers as a Case Study

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The final features of natural fiber composites (NFCs) depend on the integrated characteristics of their constituents. In the industry today, natural agro waste fibers are evaluated using a limited number of criteria. In this work, a combined multi-criteria evaluation stage technique (CMCEST) is introduced as a simple efficient systematic indicator to enhance evaluation of the available natural agro wastes for polymeric composites. In this proposed technique, criteria affecting the proper selection of natural agro waste fibers were combined and divided into sequence stages as follows: single-evaluation-criterion (SEC), combined-double-evaluation-criterion (CDEC), combined-triple-evaluation-criterion (CTEC), *etc.* These stages are based on combined physical, mechanical, and economic evaluation criteria and can be extended to several further stages to include other beneficial characteristics. The effectiveness of this technique was demonstrated by evaluating coir, date palm, jute, hemp, kenaf, and oil palm fibers simultaneously. This combined evaluation criteria can lead to more informative decisions regarding selection of the most suitable fiber type for polymeric composites. The CMCEST enhancements can reveal new potential fiber types through better evaluation schemes, help achieve clearer indications of the capabilities of available agro wastes to enhance composites, and determine proper ecological waste management practices. Utilizing the proposed technique, the date palm fiber type was found to be quite promising due to beneficial characteristics revealed in CTEC, which provides a reasonable, cheap, and eco-friendly alternative material suitable for different applications.

Keywords: Natural fiber composites; Combined evaluation criteria; Agro wastes; Date palm fibers; Waste management practice; Mechanical properties

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INTRODUCTION

Proper waste management and utilization have recently become essential for both industrial sustainability and the environment. Large quantities of agro waste fibers are accumulated annually without any benefit, and some of them are burned (AL-Oqla and Sapuan 2014c). This dramatically enhances environmental pollution as well as ecological problems. Moreover, utilizing partial agro waste types in useful applications and ignoring others encourages the improper utilization of available natural resources and leads to the destruction of the ecological balance through unplanned consumption (Zhang and Matsuto 2011; Louwagie *et al.* 2012). Thus, more efforts in valorizing available natural resources as well as wastes through finding proper evaluation indicators to clarify their capabilities for industrial applications can enhance solving such problems, reveal new potential applications to rebalance the undesirable consumption, and determine proper ecological waste management practices (Zhang and Matsuto 2011; AL-Oqla and Sapuan 2014c).

Selecting the appropriate material type for a particular application can enhance customer satisfaction attributes and utilize successful sustainable practices (AL-Oqla and Sapuan 2014c). The adoption of new materials as well as bio-composites in a specific industrial sector is influenced by several constrains and limitations (Dweiri and Al-Oqla 2006; Al-Oqla and Sapuan 2014c), which makes it a complex matter. Thus, proper material evaluations have to be performed and decisions have to be drawn utilizing the proper pairwise comparisons and decision-making tools that are currently implemented in different engineering applications (Dweiri and Al-Oqla 2006; AL-Oqla and Hayajneh 2007; AL-Widyan and AL-Oqla 2011; Al-Oqla and Omar 2012; AL-Widyan and AL-Oqla 2014; Malekmohammadi and Rahimi Blouchi 2014).

Natural fiber composites as eco-friendly, cheap materials have recently received much attention due to the continuous emphases on industrial sustainability and environmental issues (Puglia *et al.* 2003; Luz *et al.* 2010; Vilaplana *et al.* 2010; Bajpai *et al.* 2012; Rajendran *et al.* 2012; Sapuan *et al.* 2013; AL-Oqla and Sapuan 2014a; AL-Oqla and Sapuan 2014b). The use of such materials has been encouraged in various industrial applications because of their desirable characteristics, including their light weight, high specific properties (like specific strength and modulus), low cost, ease of manufacturing, recyclability, and degradability characteristics (Alawar *et al.* 2009; Hoang *et al.* 2010; Dittenber and GangaRao 2011; Kalia *et al.* 2011; Rajendran *et al.* 2012; AL-Oqla and Sapuan 2014c). The capabilities and appropriateness of NFCs for different applications have been investigated in several works with various natural fiber types and polymer matrices (Abu-Sharkh and Hamid 2004; Al-Kaabi *et al.* 2005; Alawar *et al.* 2009; Mir *et al.* 2010; Tajvidi *et al.* 2010; Shi *et al.* 2011; Abdal-hay *et al.* 2012; Zaman *et al.* 2012; Sapuan *et al.* 2013). Properties of both individual constituencies (polymer and fillers) as well as their interfacial bonding efficiency dramatically influence the final performance and characteristics of NFCs. A wide range of valuable criteria for selecting natural fiber composites has been discussed by AL-Oqla and Sapuan (2014c), who presented levels for selecting NFCs and their products according to natural fiber properties (NFP), polymer base properties (PBP), composite characteristics (CC), and composite performance (CP).

Date palm trees are considered one of mankind's oldest cultivated plants. These trees are available in several countries around the world, particularly in the Arabian Peninsula, and have played an important role in the day-to-day life of people for a long time (Alshuaibi 2011; Al-Oqla and Sapuan 2014c). Today, the worldwide production and utilization of the date palm fruits (dates) are continuously increasing (Alshuaibi 2011). Major date-producing countries include Saudi Arabia, Egypt, UAE, Algeria, and Iran. Date palm trees annually produce large quantities of agricultural waste and fibers that can be considered a renewable source of cellulosic materials and can be utilized in various industries, particularly natural fiber polymeric composites. According to AL-Oqla and Sapuan (2014c), each date palm tree annually produces about 35 kg of residues, and about one million metric tons of date palm biomass is wasted in Saudi Arabia every year as a result of seasonal trimming of the palm tree. Moreover, these authors estimated the annual worldwide production of date palm fibers to be around 4200 metric tons. These quantities of date palm agro wastes are considered as environmental waste problem issue. Thus, implementing such wastes in natural fiber composites can not only lead to new classes of composites in terms of good mechanical and cost criteria, but also contribute to better environmental performance and the reduction of pollution, as well as proper waste management procedures. Date palm fibers have several advantages that enable them to be used in natural fiber composites (Al-Kaabi *et al.* 2005; Mahdavi *et al.* 2010). These advantages include their availability, low cost, low density, the acceptable cellulose / lignin ratio, and their high mechanical properties with respect to cost ratio (AL-Oqla and Sapuan 2014a; AL-Oqla and Sapuan 2014c).

To date, proper evaluation of natural fibers for industrial applications has not been adequately discussed regarding a wide range of desired criteria (Tahir *et al.* 2011; Zini and Scandola 2011; AL-Oqla and Sapuan 2014b; AL-Oqla and Sapuan 2014c). There is little work that addresses multiple criteria to evaluate and/or select the available natural fibers (Majumdar et al. 2004; Majumdar 2010; Monteiro et al. 2011; Ghosh and Das 2013; AL-Oqla and Sapuan 2014b; AL-Oqla and Sapuan 2014c); typically only single criteria like tensile strength, Young's modulus, elongation to break, cost ratio, uniformity index, as well as a few specific criteria like specific strength, specific modulus of elasticity, and tensile strength per unit cost are evaluated. Although AL-Oqla and Sapuan (2014c) introduced only one combined criteria in evaluating natural fibers (*i.e.*, specific modulus of elasticity to the cost ratio), no previous work introduced a systematic procedure to evaluate available agro wastes based on a combined multi-criteria evaluation scheme that can extend to several evaluation stages to gather more realistic information and provide a clearer understanding in order to make an informative decision for selecting the proper fiber type for natural fiber composites. Subsequently, better evaluation of natural fibers as a constituent of NFCs, through proper combinations of evaluation criteria that can give clearer information about each natural fiber type are still needed.

Consequently, this work aims to introduce a simple and efficient systematic combined structure of pairwise comparison schemes as an indicator to enhance evaluation of the available agro wastes for polymeric composites to achieve proper, consistent, informative, selection decisions. This can help designers to expand their eco-friendly design possibilities, as well as provide a clearer indication of the capabilities of available agro wastes, which can lead to proper ecological waste management practices.

EXPERIMENTAL

Methods

To achieve more desirable performance of polymeric natural fiber composites, better evaluation of available natural fibers is demonstrated using a combined evaluation scheme based on the integration of combined multi-criteria evaluations, which are performed simultaneously. In the proposed combined multi-criteria evaluation stage technique (CMCEST), the criteria affecting the proper selection of natural agro waste fibers were combined together and divided into categories or stages as follows: single-evaluation-criterion (SEC), combined-double-evaluation-criterion (CDEC), combined-triple-evaluation-criterion (CTEC), *etc.* Comparisons only up to CTEC were demonstrated because results became more obvious with increasing combinations. The suggested combined evaluation criteria were proposed based on single physical, single economic, and single mechanical evaluation criteria for the first category (SEC). Combined physical-mechanical criteria were utilized in the second category (CDEC), whereas combined physical-mechanical-economic evaluation criteria were implemented in the third category (CTEC) to achieve better, more consistent, and more informative selection decisions. To illustrate the effectiveness of the proposed technique in evaluating agro waste fibers for natural fiber reinforced polymer composites, pairwise comparisons between six different natural fiber types were simultaneously performed for each proposed category. Each comparison with respect to each single proposed stage is interpreted in a separate illustration. Figure1 demonstrates the flow chart scheme and stages of the proposed CMCEST.

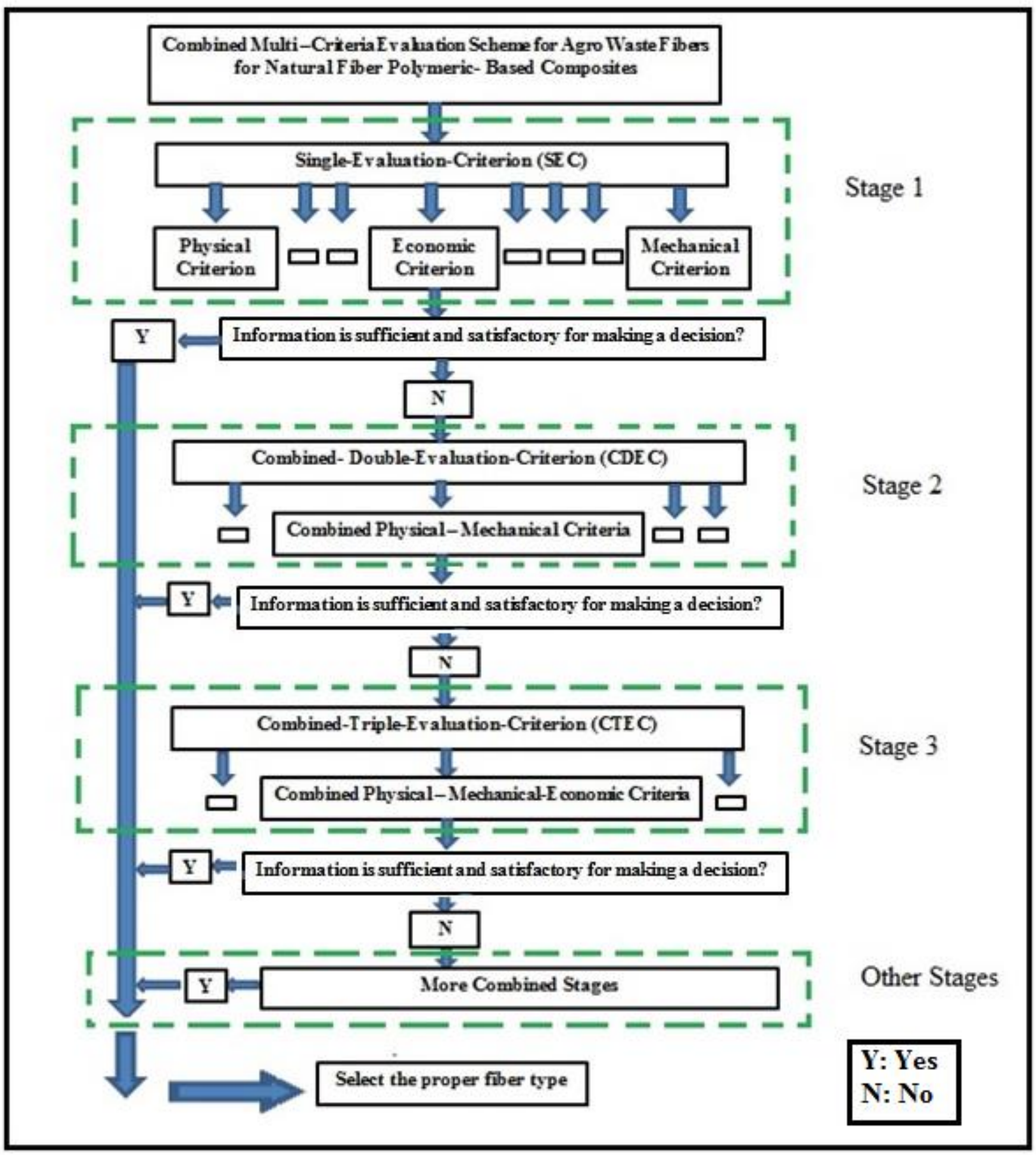

Fig. 1. Flow chart and stages of the proposed combined multi-criteria evaluation stage technique

RESULTS AND DISCUSSION

The capabilities, performance, and final attributes of NFCs depend on the physical, chemical, mechanical, and economic attributes, as well as the inherent interaction of the natural fiber composites' constituents (fibers and matrices). Thus, to maximize the benefit of such materials, investigations regarding various features and properties have to be performed as a pre-stage in any industrial application. Although a wide range of valuable criteria has been discussed by AL-Oqla and Sapuan (2014c), natural fibers have a primary role in natural fiber reinforced polymer composites. Thus, the technique presented in this work is used to evaluate six different natural fiber types, *i.e.*, coir, date palm, jute, hemp, kenaf, and oil palm. Physical, mechanical, and economic aspects were considered simultaneously. Properties of the considered fiber types and their ranges can be found in literature based on experimental work and are given in Table 1 (Dittenber and GangaRao 2011; Pilla 2011; AL-Oqla and Sapuan 2014c).

The average values were considered for comparison purposes based on the assumption that the data is equally distributed within the data range provided in the literature. To utilize this data in both CDEC and CTEC, further calculations are required. Therefore, the specific properties of the fibers (where the average values of properties were found relative to the average values of densities) were calculated and tabulated in Table 2. These values of specific properties were further measured with respect to the cost ratio as a new economic scale. Therefore, the cost ratios of the whole considered fiber types were calculated and the specific properties for each fiber type determined relative to this ratio (Table 3).

Table 1. Property Range and Average Values of the Considered Natural Fiber Types

Fiber type	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation to break (%)	Cost per weight (USD/kg)*****
Coir	1.15-1.46 (1.31)	95-230 (162.5)	2.8-6 (4.4)	15-51.4 (33.2)	0.3
Date palm	0.9-1.2 (1.05)	97-275 (186.0)	2.5-12 (7.25)	2.0-19 (10.5)	0.02
Jute	1.3-1.49 (1.4)	320-800 (560.0)	8-78 (43.0)	1-1.8 (1.4)	0.3
Hemp	1.4-1.5 (1.45)	270-900 (585.0)	23.5-90 (56.75)	1-3.5 (2.25)	1.3
Kenaf	1.4	223-930 (576.5)	14.5-53 (33.75)	1.5-2.7 (2.1)	0.5
Oil palm	0.7-1.55 (1.13)	80-248 (164.0)	0.5-3.2 (1.85)	17-25 (21.0)	0.3
Note: Average values are in parenthesis *****Dittenber and GangaRao 2011; AL-Oqla and Sapuan 2014c					

Table 2. Calculated Specific Properties and the Cost Ratios

Fiber type	Specific tensile strength (MPa)/(g/cm^3)	Specific tensile modulus (GPa)/(g/cm^3)	Specific elongation (%)/(g/cm^3)	Cost ratio*
Coir	124.05	3.36	25.34	0.231
Date palm	177.14	6.90	10.00	0.015
Jute	400.00	30.71	1.00	0.231
Hemp	403.45	39.14	1.55	1.00
Kenaf	411.79	24.11	1.50	0.385
Oil palm	145.13	1.64	18.58	0.231

Example: Coir fiber has an average density of 1.31 and an average tensile modulus of 4.4, so the specific tensile modulus is 4.4/1.31 = 3.36
*Cost ratios were found relative to the highest cost per weight (1.3); for example coir has a cost ratio of 0.3/1.3 = 0.231

Table 3. Calculated Specific Properties / Cost Ratios

Fiber type	Specific tensile strength (MPa)/(g/cm^3)/ cost ratio	Specific tensile modulus (GPa)/(g/cm^3)/ cost ratio	Specific elongation (%)/(g/cm^3)/cost ratio
Coir	537.01	14.55	109.70
Date palm	11809.33	460.00	666.67
Jute	1731.60	132.94	4.33
Hemp	403.45	39.14	1.55
Kenaf	1069.58	62.62	3.90
Oil palm	628.27	7.10	80.43

Example: The specific tensile strength of coir from Table 2 is 124.05 and its cost ratio is 0.231, so the specific tensile strength to cost ratio is 537.01

Comparisons Based on Single-Evaluation Criterion (SEC)

Comparison regarding a single physical evaluation criterion

A comparison of the densities of different natural fiber types was performed, as illustrated in Fig. 2. It is clear that date palm fibers have the smallest value of the compared fiber types. This enables date palm fibers to produce lighter products oriented to the automobile industry, as well as aerospace applications. Moreover, this comparison demonstrates the similarities of jute, kenaf, and hemp densities, which gives them similar priorities regarding this SEC. Although this comparison results in a primary value for date palm fibers, better information regarding other SEC may lead to other results for the evaluated fiber types.

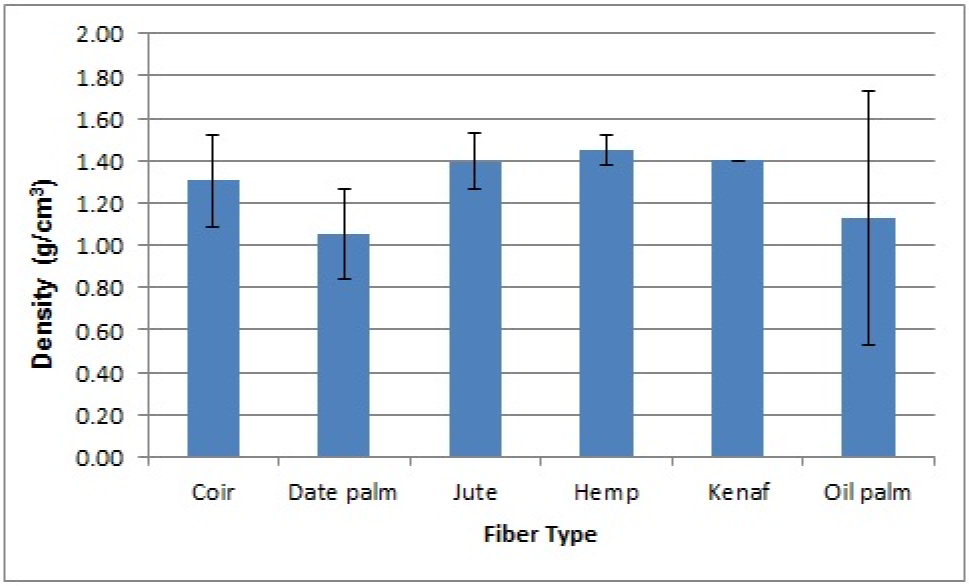

Fig. 2. Comparison of natural fibers with respect to their densities (mean ± standard deviation)

Comparison regarding a single economic evaluation criterion

A comparison of natural fibers regarding the cost ratio as another SEC, shown in Fig. 3, clearly demonstrates that date palm fiber type is the cheapest natural one among all the others. This makes it very competitive from an economic point of view. Furthermore, this SEC demonstrates a noticeable variation between hemp, kenaf, and jute. Thus, this SEC provides more information about the evaluated fiber types, but does not clearly lead to a decision regarding the best natural fiber type. Therefore, more precise information is needed to obtain more realistic results, either with more SECs or a new combined evaluation criterion.

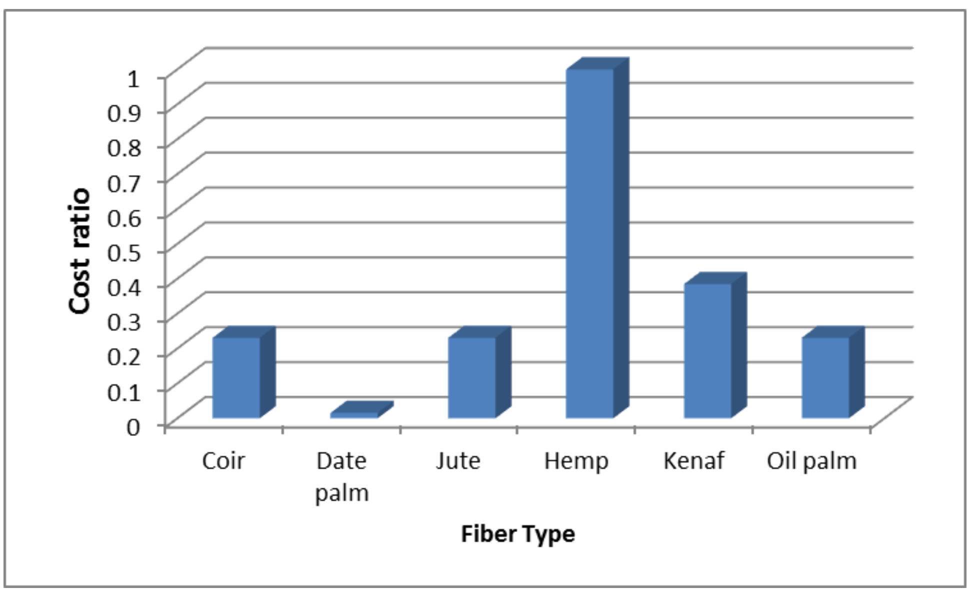

Fig. 3. Comparison of natural fibers with respect to the cost ratio

Comparison regarding a single mechanical evaluation criterion

Comparisons between different natural fiber types were performed regarding their mechanical tensile properties, as illustrated in Fig. 4.

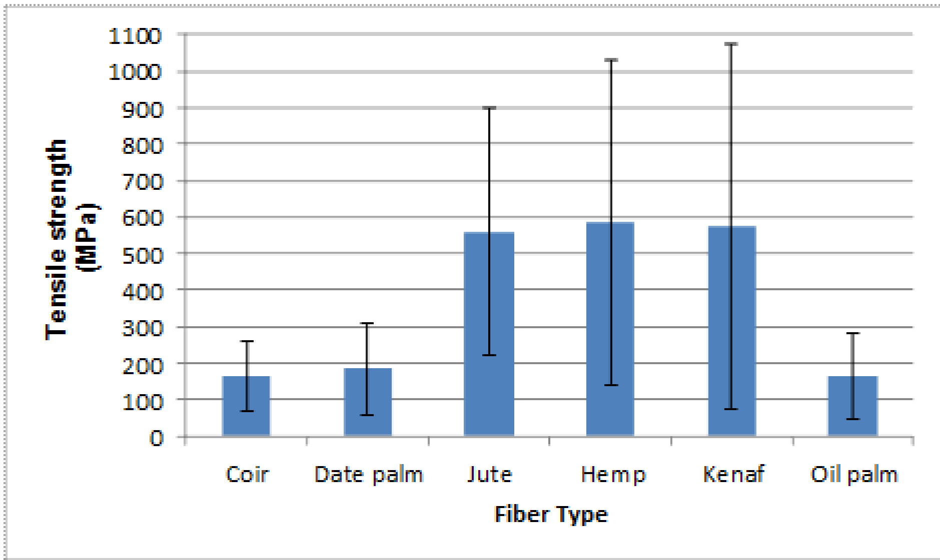

Fig. 4. Comparison of natural fibers with respect to their tensile strengths (mean ± standard deviation)

It is obvious in the figure that natural fibers vary in their mechanical properties. They can be divided into two categories; hemp, kenaf, and jute in one category, with average tensile strengths of more than 500 MPa, and date palm, oil palm, and coir in the second category, with values of less than 200 MPa. In this SEC, hemp is the most preferable type, followed by kenaf and jute, whereas date palm, coir, and oil palm are not as preferable. These results contradict the results obtained from the two previous SECs. That is, this extra SEC provided important information about one criterion for the evaluated fibers but made the selection of the most appropriate fiber type more complex. Consequently, more SECs may lead to a variation in results, rather than giving clear results. Thus, a new stage of the CMCEST is needed.

Comparisons based on Combined Double-Evaluation Criterion (CDEC)

Combined mechanical-physical evaluation criterion

Although some single-criterion comparisons can give primary information regarding the available natural fiber types for natural fiber composites, combined evaluation criteria can give more obvious indications of their appropriateness. To proceed from the above single-criterion comparisons, the same mechanical property (tensile strength) is utilized in CDEC comparisons. Consequently, the tensile strength of each single natural fiber type relative to its density (*i.e.*, the specific strength property) is compared in Fig. 5.

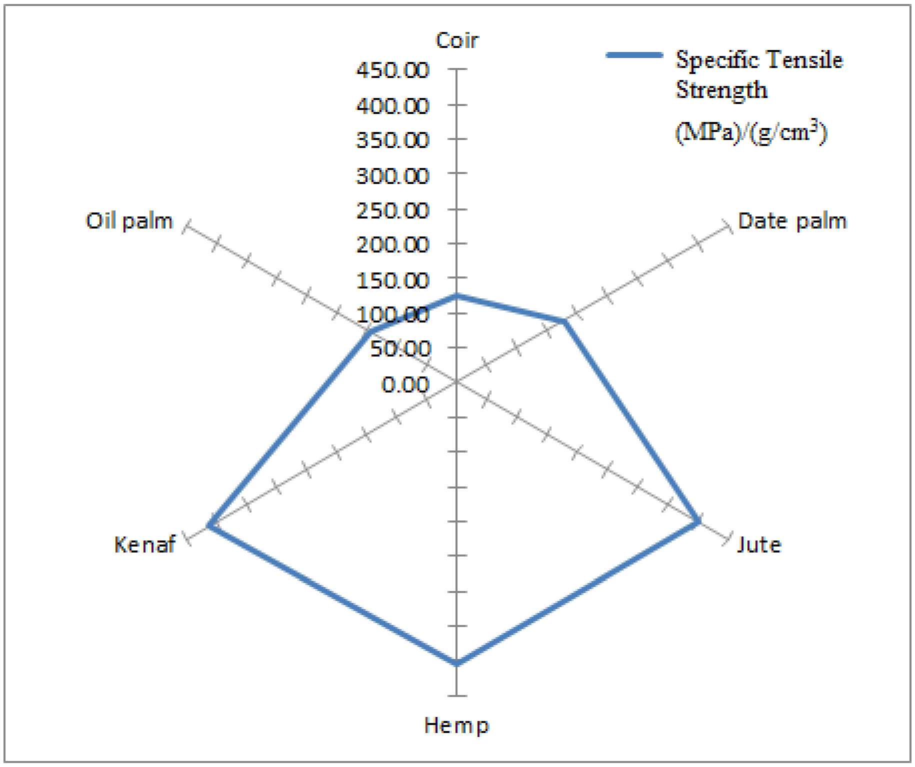

Fig. 5. Comparison of natural fibers with respect to their specific tensile strengths

Based on the combined physical-mechanical properties, kenaf seems to be slightly more preferable than hemp and jute, while date palm is more preferable to coir or oil palm. Again, this comparison slightly changes the priority of the hemp, kenaf, and jute from that of the SEC regarding the mechanical property, but does not influence the order of date palm, oil palm, and coir. This demonstrates that there is not enough gathered information to make a confident decision at the current evaluation stage, and a higher combined evaluation stage is still needed (Fig. 1).

Comparisons based on Combined Triple-Evaluation Criterion (CTEC)

Comparisons based on combined mechanical-physical-economic evaluation criterion

The CTEC stage is demonstrated in Fig. 6, where combined physical, mechanical, and economic criteria are utilized simultaneously. Integration of the physical, mechanical, and economic properties of the available natural fiber types can lead to more realistic decisions regarding the best fiber type. That is, the simultaneous evaluation of the available agro waste fibers from physical, mechanical, and economic points of view can change the priority and appropriateness of the available natural fiber types for a particular natural fiber composite application. Here, the economic point of view is integrated with other properties to capture the theme of industrial sustainability and low-cost production. Figure 6 shows a comparison of the natural fiber types, utilizing the combined physical, mechanical, and economic evaluation criterion. Here, the cost ratios of the considered fiber types were calculated and the specific tensile property (which was used double-evaluation criterion) divided by this ratio. It can clearly be seen that the specific tensile strength to cost ratio for the date palm was five times that of jute. Thus, based on this combined evaluation criterion, it can be concluded that the date palm fiber type is the most appropriate one. Similarly, a comparison of the natural fiber types using triple-evaluation criterion regarding combined tensile modulus (Fig. 7) and combined elongation to break (Fig. 8) properties show the superiority of the date palm fiber type relative to other fibers. This also demonstrates the effectiveness and novelty of the current work, which is introduced in a simple and efficient systematic manner that can ease the flow of the combined stages not provided in any previous approach. Moreover, these results demonstrate the ability of date palm fibers to enhance the industrial sustainability of any particular application. That is, it is a more reasonable low-cost and eco-friendly alternative material compared to the other natural fiber types. There is no need for extra combined evaluation criterion stages due to the obvious information gathered from the CTEC. That is, further evaluation criteria will not add valuable information or change the priority of the date palm compared with the other considered fiber types due to the large differences between the date palm fibers and the next closest fiber type. It is worthy to note that CMCEST can be extended to further stages, where evaluation aspects such as chemical, biological, and environmental characteristics can be included if more information regarding such criteria are necessary. Moreover, implementing date palm agro wastes in natural fiber composites can lead not only to new classes of composites in terms of mechanical and cost criteria, but also can contribute to better environmental performance and reduced environmental waste. Date palm fibers can dramatically enhance the sustainability of any particular application because of the characteristics revealed in the combined triple-evaluation criterion of the CMCEST, which enables it to be a reasonable cheap eco-friendly alternative type of material suitable for different industrial applications (*e.g.*, automotive, furniture, and packaging) compared with other natural fiber types.

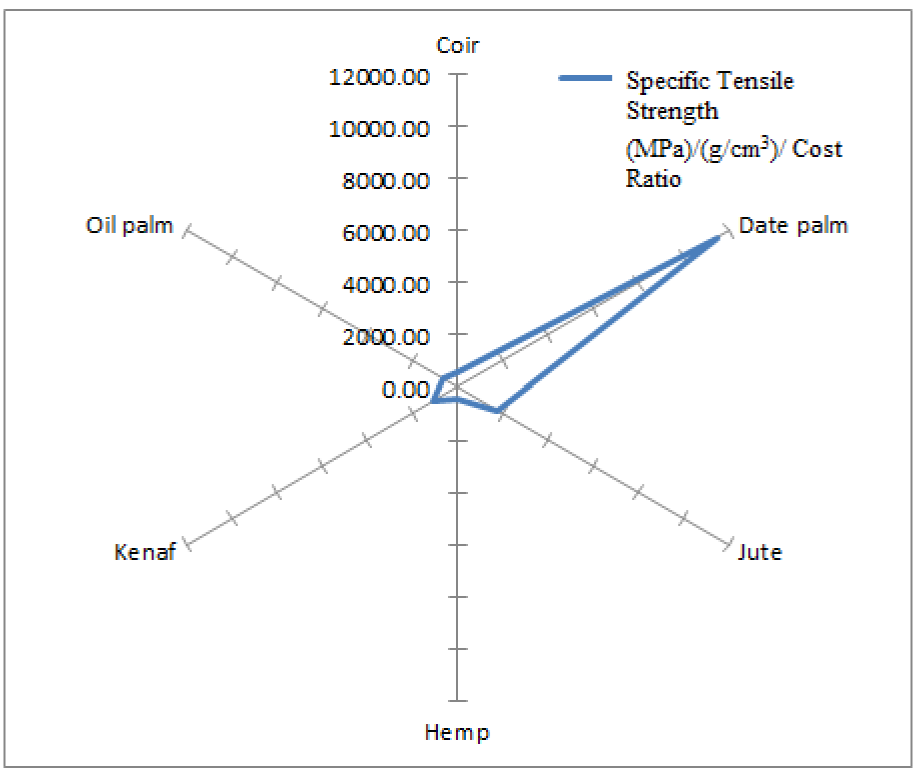

Fig. 6. Comparison of the natural fiber regarding the tensile strength to cost ratio as a combined mechanical-physical-economic criteria

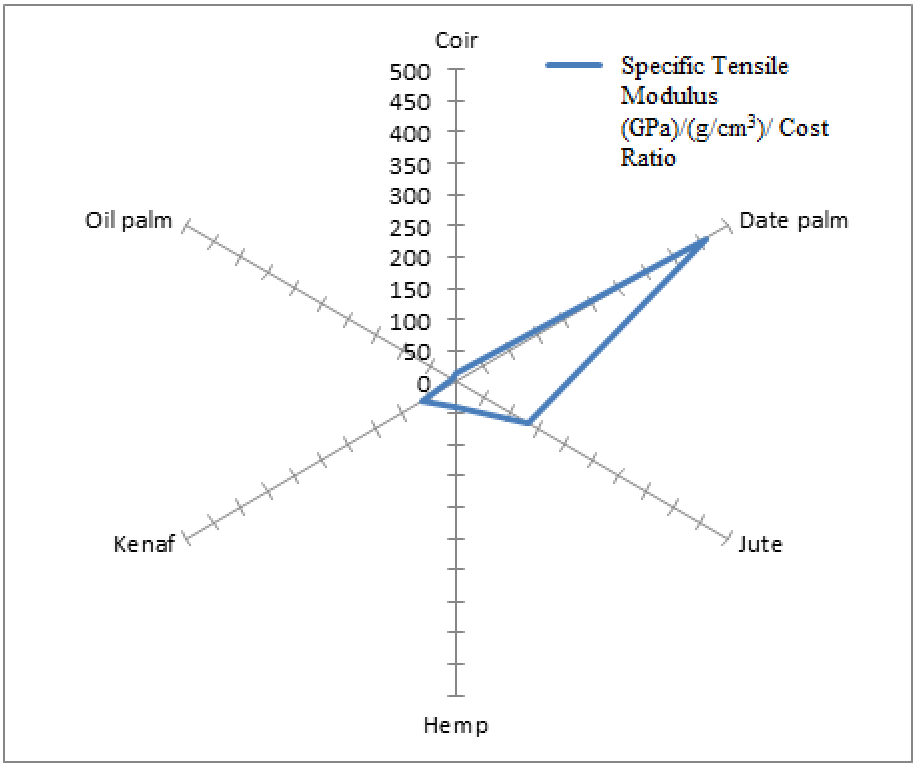

Fig. 7. Comparison of the natural fiber regarding the tensile modulus to cost ratio as a combined mechanical-physical-economic criteria

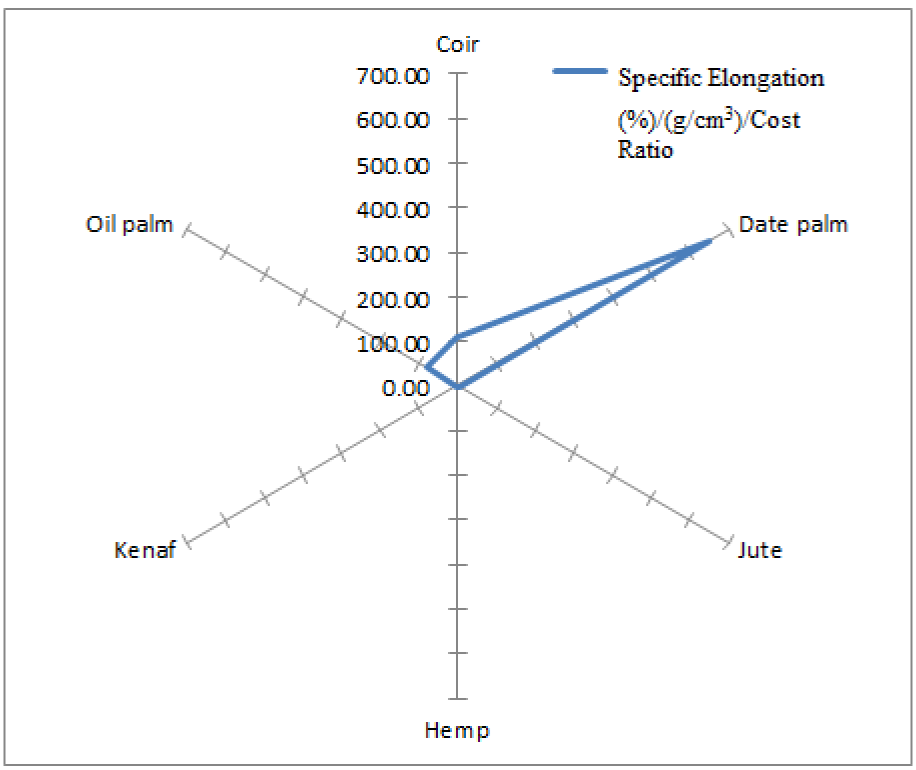

Fig. 8. Comparison of the natural fiber regarding the elongation to cost ratio as a combined mechanical-physical-economic criteria

CONCLUSIONS

1. The effectiveness of the proposed combined multi criteria evaluation stage technique (CMCEST) was successfully demonstrated by evaluating six different natural fiber types.
2. Combined evaluation based on mechanical-physical-economic properties can give clear information and can lead to better evaluation of the available agro waste fibers for polymeric composites.
3. The best evaluation of natural agro waste fibers was satisfactorily achieved in the combined triple-evaluation criterion stage of the introduced technique, where CMCEST provided more informative decisions regarding the suitable natural fiber type for NFCs.
4. The potential and appropriateness of relatively new fiber types (like date palm fiber) for NFCs can be revealed utilizing CMCEST.

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