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MATERIAL AND CURVATURE OF THE OIL PALM HARVESTING KNIFE AND THEIR EFFECTS ON FORCE AND ENERGY REQUIREMENTS

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ABSTRACT

Oil palm is an economically important crop, and the process of harvesting its fruit constitutes a major proportion of the production cost. Using an efficient harvesting knife can reduce the cultivation cost and ensure a high yield. In this study, the effect of the material and curvature of the knife for cutting fronds and fresh fruit bunches (FFB) was investigated. Three different materials, namely, EN-42J (M_1), EN-9 (M_2), and hardened and tempered (H&T) (M_3) steel and five different curvatures namely, Malaysian model (B_1), Andhra model (B_2), Kerala model (B_3), FMD-1 (B_4) and FMD-3 (B_5) were examined. A total of 15 harvesting knives were developed and evaluated in the field using a load cell indicator attached between the pole and the harvesting knife. The parameters of maximum cutting force (CF_c) , maximum specific cutting force (SCF_c), and maximum specific cutting energy (SCE) were calculated. The findings indicated that the material of the knife exhibited a negligible effect, but the curvature had a significant effect. Of the various models tested, the values of the CF_c (30.56, 54.50 kgf), SCF_c (0.26, 0.95 kg cm^{-2}), and SCE (5.08, 4.78 kg·cm cm^{-2}) were the least for the Malaysian model followed by FMD-3 model for cutting the frond and FFB.

Keywords: harvesting knife, load cell indicator, oil palm harvesting, specific cutting energy, specific cutting force.

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INTRODUCTION

The oil palm is an economically important crop and contributes to ensuring world food security; moreover, it has emerged as a renewable energy source (Hashim et al., 2012; Henson, 2012; Khatun et al., 2017; Zahari et al., 2015). Globally, oil palm production reached 416.39 million tonnes from 28.91 million hectares of plantation, with an average production of 14.41 t ha^{-1} (Food and Agriculture Association [FAOSTAT], 2023). In India, the area under oil palm is 0.37 million hectares, with a production of 16.89 million tonnes. Among the various states in India, the area under oil palm (32,982 ha) is the highest in Tamil Nadu, followed by Andhra Pradesh and Karnataka, amounting to a production of 3,038 t (Anonymous, 2021). Across all the cultivation stages of oil palm after its maturity, the harvesting stage is associated with the highest production cost (Law et al., 1992). This stage involves important activities, viz., cutting the fronds and fresh fruit bunches (FFB), stacking the fronds, collecting the loose fruits, and carrying the harvested fruits to the collection point (Henson, 2012; Jelani et al., 1998). The harvesting of oil palm constitutes approximately 32% of the overall production cost, followed by 33% for applying fertilisers (Law et al., 1992).

Efficient harvesting of FFB is crucial for ensuring the quantity and quality of FFB. A minimum ripeness standard of five detached fruits per bunch at 10-day harvesting intervals has been reported to be suitable and effective for producing FFB of the desired quality (Teo & Tan, 1992). Although some standards are available, no single standard is appropriate for different scenarios. Even within the same plantation, varied standards must be adopted based on changes in palm age, height, topography and weather. A good harvesting standard provides the best compromise among oil yield, oil quality and harvesting cost and involves the accurate determination of minimum ripeness standard, harvesting interval, harvesting techniques and procedures.

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A sickle attached to an elongated pole made from long bamboo sticks was previously used as the oil palm harvesting knife. Since 1986, aluminium poles have been used for harvesting the oil palm as a substitute for bamboo poles as they became scarce and expensive (Hassan et al., 1988). Chisels were employed widely for cutting fruits from young and short oil palms, and sickle-shaped knives with an aluminium pole were used for cutting fruits from tall oil palms. As it was lightweight and allowed telescopic adjustments, the aluminium pole-attached sickle was easier to operate than the bamboo pole-attached sickle. The harvesting capacity of the sickle attached to the aluminium pole was in the range of 0.4–1.0 man-day t^{-1} of FFB. This value depends on the age of the oil palm, harvesting season, skill of the harvester, and field topography (Omereji, 1994). The reaction force and energy requirement of harvesting knives determine their efficiency. These parameters were tested using spring-powered sickle cutters with cutting angles of 90°, 60°, and 45° at three levels of frond maturity. The findings indicated that the cutting angle rather than frond maturity exerted considerable effects on the specific reaction force and energy requirement. The cutting angle increased from 45° to 90°, and the specific reaction force increased to approximately 72% (Jelani et al., 1999). The Malaysian Palm Oil Board (MPOB) developed a motorised cutter for harvesting FFB at < 4.5 m from the ground level (Jelani et al., 2008). Field trials revealed that the harvesting capacity of the cutter was 560–750 bunches per day. Furthermore, the use of this cutter reduced the labour cost by 50%. In addition, Abbood (2020) experimented to determine the minimum cutting force requirement for cutting date palm fronds. A triangle-type knife with an edge angle of 20°, a width of 0.05 mm, and a length of 12 cm was tested with a hydraulic machine at three levels of moisture, namely, 5%, 10% and 40% and three cutting angles, namely, 0°, 45° and 90°. The cutting angle of 90° resulted in the lowest cutting force of 6.04 KN at 10% fronds water content. Shokripour et al. (2012) developed a harvesting mechanism for oil palm FFB, which involved the design of a blade tooth for rapid and clean cutting. In designing the blade, the parameters of metal type, width, blade set, thickness, tooth form, and blade length were considered. The contact angle between the saw tooth and the material was a key factor in ensuring the effective cutting performance of the saw blade. The energy consumption of the circular saw-cutting process of oil palm fronds was measured (Sun & Zaidi, 2023). A theoretical model of work and power was developed and applied to optimise the cutting process of an oil palm frond with a base width of 100 mm. A minimum cutting energy of 330 J for a rotational speed of 1,000 rpm and a feed rate of 10 mm s^{-1} was measured during the harvesting process. Although promising results were obtained in developing an effective cutting edge, economically, the device could not compete with existing manual tools.

Conventionally, harvesting knives are fabricated without considering the physical properties of the material, reaction force, cutting method, cutting angle, and cutting speed, which leads to the inefficient operation of such harvesting knives. The cutting of fronds and harvesting of FFB is a labour-intensive operation, and skilled labour is required. Moreover, the harvesting operation is time-bound as the FFB should be processed within 24 hr after harvest to obtain edible quality of raw palm oil (Arumugan & Sundaresan, 1992). The migration of labourers from rural areas to various scholastic jobs in the urban sector has made oil palm harvesting a tiresome process for the planters. This situation has necessitated the introduction of improved knives for harvesting the oil palm. The pertinent factors that influence the performance of oil palm harvesting knives are the material and the curvature of the knife (Jelani et al., 1998). In this study, the effect of the material and shape of the knife on the force and energy required for oil palm harvesting was investigated.

MATERIALS AND METHODS

Preliminary information was collected on various types of harvesting tools used in different parts of the world. Areas within Tamil Nadu and other states were visited to gain knowledge about oil palm grooves, knives, and methods used for harvesting. Among the world's countries, Malaysia is one of the major producer of palm oil. In India, Andhra Pradesh, Tamil Nadu, and Kerala are the leading states that cultivate oil palm intensively. Hence, details were collected on conventional tools used in Malaysia, Andra Pradesh, and Kerala. In Tamil Nadu, the Department of Farm Machinery and Power Engineering, Tamil Nadu Agricultural University (TNAU), conducted study on the knife used to harvest oil palm. Six different knife curvatures, namely, FMD-1, FMD-2, FMD-3, FMD-4, FMD-5 and FMD-6 were considered, and two curvatures, i.e., FMD-1 and FMD-3 were optimised based on the minimum force required to harvest oil palm. Hence, five different curvatures were selected for the investigation, which included Malaysian model (B_1), Andhra model (B_2), Kerala model (B_3), FMD-1 (B_4) and FMD-3 (B_5) (*Figure 1*).

The five knives differed in their shape, width and height. The detailed specifications of oil palm harvesting knives are presented in *Table 1*, and the dimensions are illustrated in *Figure 2* (Singh, 2012).

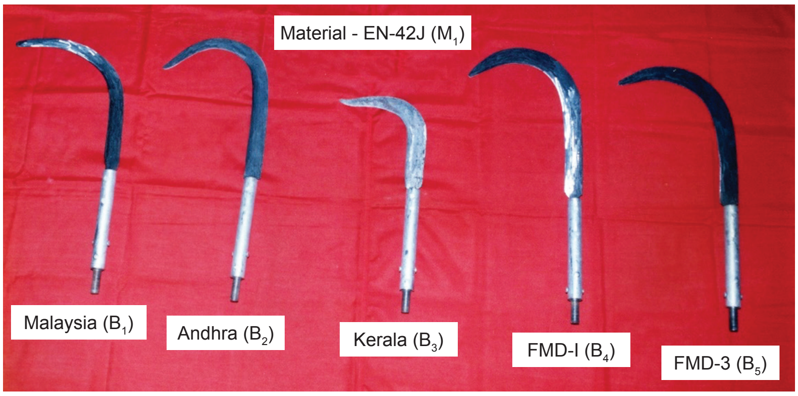

Figure 1. A view of the five types of knife curvatures selected.

TABLE 1. DIMENSIONS OF THE STUDIED OIL PALM KNIVES

Parameters	**Dimensions of sickles (mm)**				
	Malaysia (B_1)	**Andhra (B_2)**	**Kerala (B_3)**	**FMD-1 (B_4)**	**FMD-3 (B_5)**
Maximum width of the knife (B)	38	39	50	44	45
Knife thickness (C)	4	4	4	4	4
Cutting surface (D)	450	516	302	472	456
Outer length of the knife (E)	555	608	418	631	589
Concavity of the knife (F)	136	182	98	157	135
Sickle length (G)	634	664	535	676	651
Maximum handle length (H)	300	300	300	300	300
Maximum handle diameter (I)	31.25	31.25	31.25	31.25	31.25
Size of the sickle (L)	388	352	281	380	403

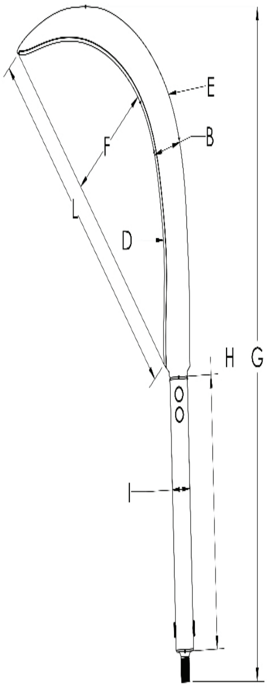

Figure 2. Dimensions of the oil palm knife.

The hardness of the knife material plays a vital role in determining the energy consumed for harvesting the FFB and cutting the fronds (Zhang et al., 2023). Material hardness is mainly based on the chemical composition and carbon content present in it (Trzaska & Sitek, 2023). Three different materials commonly used for manufacturing the harvesting knife namely EN-42J (M_1), EN-9 (M_2) and hardened and tempered (H&T) steel (M_3) were selected for the investigation in which the percentage composition of carbon, silicon, and manganese was studied (Singh et al., 2022). The details of the chemical composition analysis of the abovementioned four materials are described in *Table 2*.

TABLE 2. METALLURGICAL COMPOSITION OF THE SELECTED MATERIALS

Material	**Carbon %**	**Silicon %**	**Manganese %**
EN-42J	0.58	0.20	0.69
EN-9	0.55	0.05	0.77
H&T Steel	1.10	0.09	0.76

Hence, this study was conducted using five different curvatures, viz., B_1, B_2, B_3, B_4 and FB_5 made of three different materials, namely, M_1, M_2 and M_3. Using all possible combinations of the materials and curvatures selected, a total of 15 knives were developed and evaluated in the field.

Measurement of the Force Using Load Cell Indicator

The harvesting knives were evaluated in one of the largest private oil palm plantations located in Upparpatti, which is approximately 6 km from Theni toward Cumbam, India. This plantation was established in 1994 with 600 oil palms over an area of 10 acres. Presently, the total area under oil palm in this plantation is approximately 160 acres. The assessment was performed on a 10-years-old oil palm having an average height of 4.3 m.

The handle of the knife was made by inserting a wooden roller in an aluminium pipe 31.25 mm in diameter, 2.50 mm in thickness, and 270.00 mm in length. The knife handle was inserted into it and riveted using aluminium rivets at four different positions. The aluminium handle was provided with a threaded collar, which allowed the attachment and detachment of the sickle to the aluminium pole. The handle of the knife was threaded to one end of the load cell, and the other end was threaded to the pole. Subsequently, the load cell was connected to the load cell indicator with a long cable (*Figure 3*). The strain gauge-type load was used to measure the cutting force (Kathirvel et al., 2009, 2011). The knife was attached to or detached from the aluminium poles of various lengths as per the requirement, i.e., the height of the oil palm. The pole was of three different lengths, i.e., 3.60, 2.10 and 1.50 m. A combination of poles was also used depending on the height of the oil palm.

After setting up the harvesting knife with the instrument, the cutting operation was performed by the operator. Harvesters with comparable skill and experience (10 years) in oil palm harvesting were used in this study. The harvesting of oil palm fruits involves two activities: The first one is to lift the pole upright and the second is to cut the fronds and fruit bunches. The readings were noted from the load cell indicator when the operator cut the fronds in a single stroke. Trained operators usually cut the fronds and FFB in the first attempt itself. After cutting the frond, its exposed cut surface was traced on a plain sheet and the area of the cut surface was measured using a polar planimeter and its depth using a vernier calliper. With the same setup, the knife was used to harvest the FFB of the oil palm. The readings were noted from the load cell indicator when the operator cut the FFB in a single stroke. A total of 3–4 fronds must be cut to reach the peduncle of the FFB. The operational view of harvesting FFB is shown in *Figure 4*. The exposed area of the peduncle and the depth of the cut were measured using a polar planimeter and vernier calliper, respectively. After cutting the fronds and FFB with the selected knife, the same procedure was repeated for all developed knives. Each treatment was replicated eight times for cutting the fronds and four times for harvesting the FFB for statistical analysis to obtain accurate results.

Evaluation of the Parameters

The parameters used to evaluate the selected knives were maximum cutting force (CF_c), maximum specific cutting force (SCF_c) and maximum specific cutting energy (SCE) (Jelani et al., 1998; Persson, 1987; Prasad & Gupta, 1975).

Maximum cutting force (CF_c). CF_c between the pole and the knife is defined as the maximum force exerted by the operator for cutting the fronds or harvesting the FFB. The value of this force directly affects the cutting performance and the drudgery involved in harvesting.

The average of the readings recorded from the load cell indicator was calculated and compared

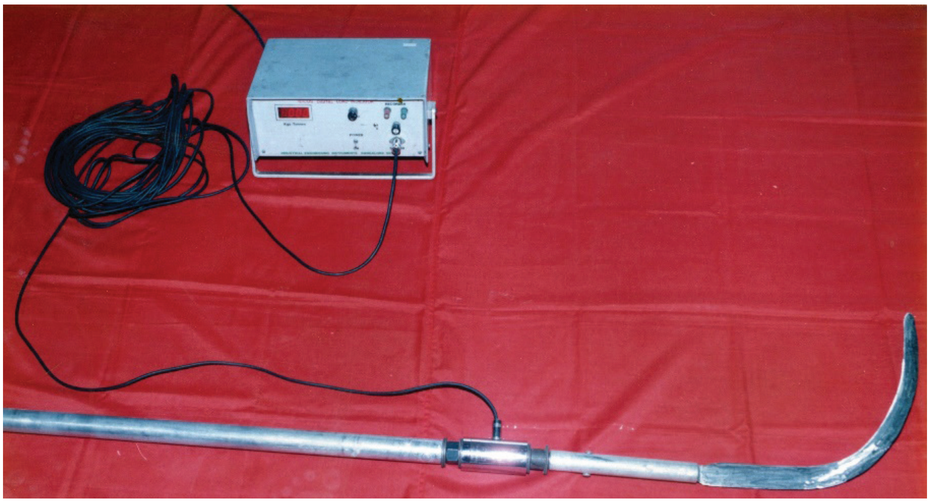

Figure 3. A view of the load cell and indicator connected between the pole and the knife.

Figure 4. The harvesting of FFB.

with the calibration chart. The corresponding load cell indicator readings from the calibration chart directly provided the maximum cutting force required by the operator for cutting the FFB.

Maximum specific cutting force (SCF_c). The SCF_c is defined as the maximum value of the cutting force per unit cross-sectional area of the material under the knife [Equation (1)]. The area of the cut varies with the approach angle for cutting the FFB, which in turn affects the cutting performance directly through the specific cutting force.

$$SCF_c = F/A \tag{1}$$

where, SCF_c is the maximum specific cutting force (kg cm^{-2}), F is the force (kg), and A is the area of the cut (cm^2).

The exposed cut area of the frond was calculated based on the recorded dimensions. Similarly, the area of the cut surface of the peduncle of FFB was calculated from the diameter of the peduncle.

Maximum specific cutting energy (SCE). The SCE is defined as the cutting energy required to cut per unit cross-sectional area [Equation (2)]. The depth of the cut for cutting the FFB also varies with the angle at which the operator cuts the FFB. The energy required for cutting directly affects the performance of the harvesting operation.

$$SCE = (F/A) \times D \tag{2}$$

where, SCE is the maximum specific cutting energy (kg·cm cm^{-2}), F is the force (kg), A is the area of the cut (cm^2), and D is the depth of the cut (cm).

The results were analysed statistically using analysis of variance (ANOVA) with the MINITAB software. A completely randomised design was used to assess the effects of the variables, namely, material (M) and knife curvature (B), on CF_c, SCF_c and SCE.

RESULTS AND DISCUSSION

The ANOVA for CF_c, SCF_c and SCE is shown in *Table 3*. The "F" value was significant at a 1% level of probability for all treatments for CF_c, SCF_c and SCE. The main effect of the type of knife curvature (B) was significant at a 1% level of probability, which signifies that this variable influenced the CF_c, SCF_c and SCE. On the contrary, the effect of knife material (M) was insignificant.

TABLE 3. ANOVA FOR MAXIMUM CUTTING FORCE (CF_c), MAXIMUM SPECIFIC CUTTING FORCE (SCF_c) AND MAXIMUM SPECIFIC CUTTING ENERGY (SCE)

SV	DF	F		
		CF_c	SCF_c	SCE
Treatment	14	6.61**	5.87**	5.92**
Knife material (M)	2	1.82 ns	2.21 ns	< 1
Knife curvature (B)	4	15.7**	12.36**	15.51**
M×B	8	3.25**	3.55**	2.55*
Error	105			
Total	119			
CV		**29.0%**	**38.0%**	**34.5%**

Note: ** - Significant at 1% level; * - significant at 5% level; ns - not significant.

The interaction effects of material and curvature of the knife on CF_c, SCF_c and SCE are listed in *Table 4*. M_3 did not exert a significant effect on CFc, SCFc and SCE with different types of knife curvatures as the force required remained the same at all levels of the variables. The interaction effects of the treatments from the other two materials M_1 and M_2 were significant. The CF_c was the least for the combination of M_1B_1 (30.56 kgf), M_2B_1 (31.81 kgf) and M_2B_5 (32.56 kgf). The specific cutting force was the least for the combination of M_1B_1 (0.26 kg cm^{-2}), M_2B_1 (0.29 kg cm^{-2}) and M_2B_5 (0.26 kg cm^{-2}). Similarly, the maximum specific cutting energy was the lowest for the combination of M_1B_1 (5.08 kg·cm cm^{-2}), M_2B_1 (5.31 kg·cm cm^{-2}) and M_2B_5 (5.05 kg·cm cm^{-2}).

Effect of the Material

The effect of the material on CF_c, SCF_c and SCE for cutting fronds and FFB is represented in *Figure 5*. The material of the knife exerted a negligible effect on all three parameters for cutting oil palm FFB as the cutting force for each material was almost the same for the different curvatures of the knife. Hence, the material had negligible influence on the CF_c, SCF_c and SCE. This finding substantiated the results obtained from the statistical analysis that the effect of curvature of the knife on CF_c, SCF_c and SCE was significant.

Effect of Knife Curvature

The effect of knife curvature on CF_c, SCF_c and SCE for cutting fronds and FFB is represented in *Figure 6*. The knife curvature B_1 resulted in the least value (30.56, 54.5 kgf) of CF_c irrespective of the material. Apart from B_1, knife B_5 (32.56, 55.0 kgf) required the least CF_c for cutting oil palm fronds and FFB when compared with other curvatures. The knife curvatures B_1 (0.26, 0.95 kg cm^{-2}) and B_5 (0.26, 1.15 kg cm^{-2}) required the least SCF_c when compared with other curvatures. Moreover, the curvature of the knife influenced the SCE, which was predominant for knife B_5 (5.05, 4.50 kg·cm cm^{-2}) as it exhibited the least value for the SCE, followed by knife B_1 (5.08, 4.78 kg·cm cm^{-2}). All other knives were ineffective as their curvatures made the operation tedious. This difficulty could be attributed to the radius of the knife curvature matching the frond structure, which ensured easy cutting. For example, knife curvature B_3 slipped during the cutting operation owing to its right-angle curvature. This finding validated the results obtained from statistical analysis that the effect of knife curvature on CF_c, SCF_c and SCE was significant.

Optimisation of Parameters for the Selected Knives

Based on the above analysis and the results obtained, the optimum combination of the knife material with the least value for the selected parameters, viz., CF_c, SCF_c and SCE is presented in *Table 5*.

The harvesting productivity of the knives was evaluated, and the performance of the optimised values of different variables were determined. FFB harvested per day using the conventional knife was only 96 bunches, whereas those harvested per day with the modified harvesting knives were 144–147 bunches, which was 53% more than that of conventional tools.

TABLE 4. M×B TABLE OF MEANS FOR MAXIMUM CUTTING FORCE (CF_c), MAXIMUM SPECIFIC CUTTING FORCE (SCF_c) AND MAXIMUM SPECIFIC CUTTING ENERGY (SCE)

Curvatures	CF_c			SCF_c			SCE		
	EN-42J (M_1)	EN-9 (M_2)	H&T (M_3)	EN-42J (M_1)	EN-9 (M_2)	H&T (M_3)	EN-42J (M_1)	EN-9 (M_2)	H&T (M_3)
Malaysia (B_1)	**30.56 c**	**31.81 c**	44.25 a	**0.26 b**	**0.29 c**	0.34 a	**5.08 b**	**5.31 c**	6.89 a
Andhra (B_2)	46.81 b	50.06 b	45.31 a	0.36 b	0.50 b	0.38 a	7.88 b	8.83 b	7.71 a
Kerala (B_3)	48.88 b	35.13 c	37.94 a	0.40 b	0.56 b	0.38 a	7.78 b	9.46 b	7.52 a
FMD-1 (B_4)	72.94 a	67.63 a	49.81 a	0.65 a	0.76 a	0.43 a	12.81a	13.21a	9.28 a
FMD-3 (B_5)	45.44 b	**32.56 c**	47.38 a	0.39 b	**0.26 c**	0.47 a	6.93 b	**5.05 c**	8.61 a

TABLE 5. OPTIMISED PARAMETERS FOR THE SELECTED KNIVES

Knife	CF_c		SCF_c		SCE	
	Frond	FFB	Frond	FFB	Frond	FFB
EN-42J (M_1) and Malaysia (B_1)	30.56	54.5	0.26	0.95	5.08	4.78
EN-9 (M_2) and FMD-3 (B_5)	32.56	55.0	0.26	1.15	5.05	4.50

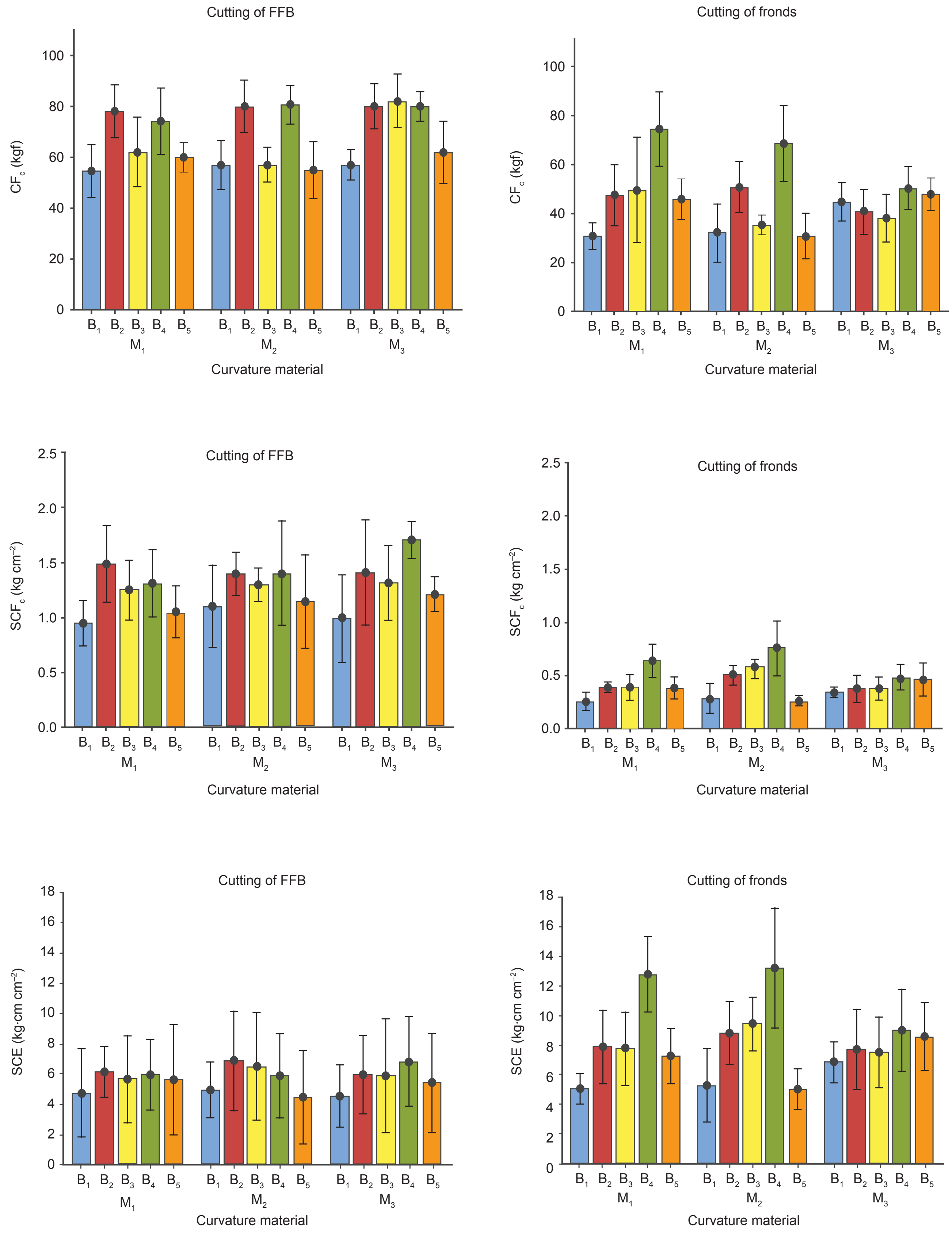

Figure 5. The effect of the material on CF_c, SCF_c and SCE for cutting fronds and fresh fruit bunches.

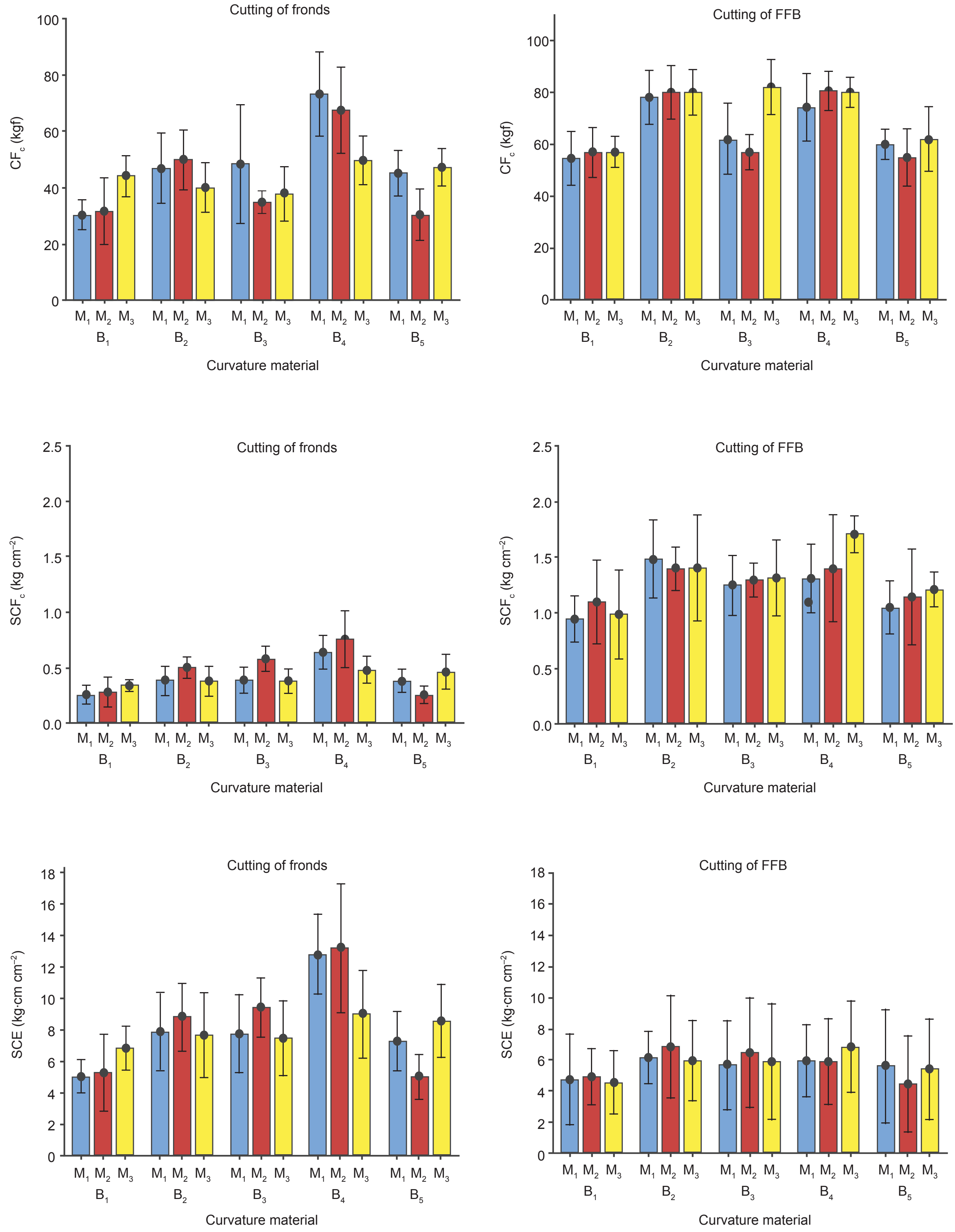

Figure 6. The effect of knife curvature on CF$_c$, SCF$_c$ and SCE for cutting fronds and FFB.

CONCLUSION

The material used to construct the knife had negligible effect on CF_c, SCF_c and SCE for cutting oil palm FFB. The least values for CF_c (30.56, 54.5 kgf), SCF_c (0.26, 0.95 kg cm^{-2}) and SCE (5.08, 4.78 kg·cm cm^{-2}) were recorded for the Malaysian model, which was followed by the FMD-3 model (32.56, 55.0 kgf; 0.26, 1.15 kg cm^{-2} and 5.05, 4.50 kg·cm cm^{-2} respectively), for cutting the fronds and FFB.

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