Original Article

Optimum design based on fabricated natural fiber reinforced automotive brake friction composites using hybrid CRITIC-MEW approach

Tej Singh
Savaria Institute of Technology, Faculty of Informatics, ELTE Eötvös Loránd University, Szombathely, 9700, Hungary

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A B S T R A C T

In this present study, the hybrid criteria importance through inter-criteria correlation (CRITIC) and multiplicative exponent weighting (MEW) optimization approach is applied to the problem of selecting an optimal brake friction formulation that satisfies maximum performance requirements. Automotive brake friction composites containing 5, 10, 15, and 20 weight percentages of natural fibers (hemp, ramie, and pineapple) were developed. These composites analyzed for tribological properties using a Chase testing machine following IS-2742 Part-4 standard. The tribological results, such as friction-fade (%), friction coefficient, friction-recovery (%), friction fluctuations, friction-variability, friction-stability, and wear, are fixed as performance attributes to identify the most suitable friction formulation. The performance coefficient of friction (0.548) and friction-stability (0.93) remain highest for 5 wt.% pineapple fiber composites. Whereas the lowest wear (1.08 g) along with the least friction-recovery (107.54%) was exhibited by 5 wt.% hemp fiber composites. The highest friction-recovery (121.56%) corresponding to the lowest friction performance (0.501) was exhibited by 20 wt.% ramie fiber added composite. On the other hand, 5 wt.% ramie fiber added composite display lowest friction-fade (22.12%) with least friction-variability (0.330) and fluctuation (0.178). The experimental results are found to be strongly composition-dependent and without any pronounced trend. Consequently, it becomes difficult to prioritize the performance of formulations to choose the best among a set of composite formulations. Therefore, a multi-criteria decision-based optimization approach called CRITIC-MEW was applied; that suggests 5 wt.% ramie fiber added composite satisfies the maximum preset performance criteria.

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1. Introduction

High friction stability, low wear and fade with excellent recovery are the main performance attributes that every material designer wants to achieve with his formulation [1,2]. Usually, friction composites are formulated based on a complex composition of disparate ingredients (binder, property modifiers, filler, fibers) with different functions that are used
in varying amounts and combinations [3–5]. Generally, fibers are used for reinforcement purpose which increases the structural integrity of the composite during braking and it helps in consolidating wear debris and act as nucleation sites for contact plateaus formation [6]. Conventionally, minerals fibers (asbestos, rock wool, wollastonite), synthetic fibers (glass, Kevlar, carbon, steel), and their combinations are used as reinforcement [1–6]. The finite availability of these resources and related health hazards are driving research in alternative materials including plant based fibres [7]. The renewability, availability, biodegradability, and eco-friendliness behaviour of plant based natural fibers make them a better option than traditionally used synthetic and mineral fibers [8–21]. The potential usage of natural fibers in automotive braking applications is investigated by various researchers. The possibility of using rattan fibers in brake friction composite formulations was assessed by Ma et al. [22] and it was found that the tribological properties remain optimal with 5 wt.% fibrous reinforcement. Fu et al. [23] concluded that the addition of 5.6 vol.% flax fibers resulted in optimal tribological properties. The highest wear resistance with good friction coefficient was recorded with 3 wt.% treated bamboo fiber reinforced polymer composites by Ma et al. [24]. Similar results were reported by Liu et al. [25], where the highest wear resistance was recorded for 3 wt.% abaca fiber-reinforced brake composites. The potential of Prosopis juliflora fiber in friction composite was investigated by Rajan et al. [26]. The authors found that chemically treatment of fibers resulted in increased thermal stability of the designed friction composite. Areva javanica fibers were also reported to replace synthetic acrylic fibers for automotive brake applications by Ahmed et al. [27]. The effect of coir fiber loading level (0–20 vol.%) in the automotive braking application was investigated by Maleque and Atiqah [28]. The authors concluded that the composite with 5 vol.% coir fibers exhibits optimal results for wear and physio-mechanical properties. Xin et al. [29] studied the effect of sisal fiber loading (10–30 wt.%) on automotive brake composites tribological properties. They reported that the 4:3 proportion of sisal fiber and resin attained an optimal combination of tribological properties. Liu et al. [30] studied the effect of corn stalk fiber loading (0–8 wt.%) on tribological and physio-mechanical properties of automotive brake composites. The study concluded that 6 wt.% corn stalk fiber-based composite exhibited optimal properties. The potential of jute fibers (0–23.6 vol.%) in combination with powdered hazelnut shells (6.3–9 vol.) in automotive brake composites was studied by Matejka et al. [31]. Authors claimed that the composite having 6.3 vol.% of powdered hazelnut shells and 23.6 vol.% of jute fibers could achieve acceptable friction coefficient stability.

The literature revealed that the amount and type of natural fibers significantly impact the final tribological properties of automotive brake composites. Therefore, designing an efficient automotive brake composite with desired tribological properties is the challenge faced by material scientists. The complexity will increase as every designed automotive brake composite has its rating for each evaluated property [32]. For selecting the optimal brake friction formulation, multiple-criteria decision-making (MCDM) techniques prove to be a robust tool and widely reported in the literature [33–37]. One such MCDM technique - criteria importance through inter-criteria correlation (CRITIC) and multiplicative exponent weighting (MEW) has been investigated by few researchers and reported in the literature [38,39]. MEW is a simple ranking technique and is easy to implement as it requires less computational time, while the CRITIC technique is used to obtain the attributes weight. Both methods are suitable for particular problems and have been successfully applied in several fields [40]. In the current study, the tribological performance data for ramie, hemp and pineapple fibre friction composites from our earlier publications [41–43] was used and CRITIC-MEW a multicriteria based optimization approach was applied to choose an optimal brake pad formulation satisfying maximum performance criteria.

### 2. Experimental work

#### 2.1. Materials and fabrication procedure

The automotive brake composites were fabricated based on a fixed composition containing phenol-formaldehyde resin (10 wt.%), vermiculite (5 wt.%), graphite (5 wt.%), lapinus fiber (20 wt.%), and aluminium oxide (5 wt.%) amounting to 45 wt.. The remaining 55 wt.% of the formulation was adjusted with barium sulphate with natural fibers, as presented in Table 1. The natural fibers (hemp, ramie, and pine-apple) were purchased from Jaipur, India. The procured natural fibers were treated with sodium hydroxide solution (5 wt.%) for 24 h at room temperature. Followed by washing with distilled water and dried in an oven at 60 °C for 5 h. Then, the fibers were cut to aaverage length of 1–6 mm as presented in Fig. 1a–c and used in the fabrication of composites.

The selected ingredients in the desired proportion (Table 1) were mixed using a shear-type mixer with a chopper speed of 3000 rpm. After that, the mixture was compressed to

### Table 1 – Grading of the composites.

<table>
<thead>
<tr>
<th>Ingredients (wt.%)</th>
<th>Composite code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed composition</td>
<td>FC1 FC2 FC3 FC4 FC5 FC6 FC7 FC8 FC9 FC10 FC11 FC12</td>
</tr>
<tr>
<td>Barium sulphate</td>
<td>45 45 45 45 45 45 45 45 45 45 45 45</td>
</tr>
<tr>
<td>Ramie fiber</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Pineapple fiber</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Hemp fiber</td>
<td>5 10 15 20 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Pineapple fiber</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
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</tr>
<tr>
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<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Pineapple fiber</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Hemp fiber</td>
<td>5 10 15 20 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>Pineapple fiber</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>
composites using a hot molding machine at 155 °C temperature for 10 min under 15 MPa pressure and post cured for 3 h at a temperature of 170 °C in a standard oven [41–43]. After post-curing, the composites’ surfaces were polished using a grinding wheel and then sized to 25 mm × 25 mm × 5–6 mm samples (Fig. 1d) for tribological study.

2.2. Testing procedure

The wear and friction behaviors of the manufactured automotive brake composites were determined using a Chase machine (Ducom, India) following IS 2742 part-4:1994 quality test procedure (equivalent to SAE (society of automotive engineers) J661a: 2012). The working of Chase machine and detailed test procedure was reported elsewhere [44]. According to the testing schedule, the load was applied on the composite specimen, and frictional force was estimated by a load cell connected to the sample holder. The test was initiated by burnishing, baseline-I, followed by four fade-recovery, wear, and baseline-II runs as listed in Table 2. Before each test, the drum (280 mm diameter) was polished with 320 grit size abrasive paper. To establish nearly a complete mating with the drum, composite samples were first burnished at 308 RPM for 20 min with 440 N load. After burnishing, sample weight and thickness were measured. After that, initial wear measurement (indicator reading of height of sample holder) was initiated. During this, the drum was stationary while temperature fluctuated between 88 °C and 99 °C with 660 N on the specimen. The same process was repeated for second, third and final wear measurement after recovery-I, wear and baseline-II run, respectively.

After the completion of the test, wear in terms of weight loss (g) was computed. The friction coefficient (μ) values considered in this article referred to four fade and recovery runs. The recorded μ was further analyzed for various performance properties, and alongside wear were taken as attributes for composite selection. The selected attributes are briefly described as [1,2]:

Attribute-1 (A-1): Performance coefficient of friction; μ_{P} (larger-is-better): It is the average μ value of four fade and recovery runs.

Attribute-2 (A-2): Friction fluctuations (smaller-is-better): Friction fluctuations are calculated as;

Friction fluctuations = μ_{max} − μ_{min} \hspace{1cm} (1)

![Fig. 1 – Images of natural fibers (a) Hemp, (b) Ramie, (c) Pineapple and (d) Composite samples.](image)

| Table 2 – Test procedure for tribological assessment. |
|-------------------|----------|---------|--------|-------------------|----------|--------|-------------|
| Test run         | Load (N) | On time | Off time | Temperature (°C) | Speed (RPM) | Application |
|                  |          | Min | Sec | Sec | Initial | Final |              |
| Burnish          | 440      | 20  | –   | –   | –       | 93    | 308           |
| Baseline-I       | 660      | –   | –   | –   | 82      | 104   | 411           |
| Fade-I           | 660      | 10  | –   | 20  | 82      | 289   | 411           |
| Recovery-I       | 660      | –   | 10  | –   | 261     | 93    | 411           |
| Wear             | 660      | –   | 20  | –   | 193     | 204   | 411           |
| Fade-II          | 660      | 10  | –   | –   | 82      | 345   | 411           |
| Recovery-II      | 660      | –   | 10  | –   | 317     | 93    | 411           |
| Baseline-II      | 660      | –   | 10  | 20  | 82      | 104   | 411           |
where, $\mu_{\text{min}}$ and $\mu_{\text{max}}$ are the lowest and highest $\mu$ value recorded during four fade and recovery runs.

Attribute-3 (A-3): Friction-stability (larger-is-better): It is calculated as:

\[
\text{Friction-stability} = \frac{\mu_p}{\mu_{\text{max}}} \quad (2)
\]

Attribute-4 (A-4): Friction-variability (smaller-is-better): It is calculated as:

\[
\text{Friction-variability} = 1 - \frac{\mu_{\text{min}}}{\mu_{\text{max}}} \quad (3)
\]

Attribute-5 (A-5): Friction-fade (%) (smaller-is-better): It is calculated as:

\[
\text{Friction-fade} = \frac{\mu_p}{\mu_{\text{f}}} \times 100 \quad (4)
\]

where $\mu_f$ is the lowest $\mu$ value recorded during two fade runs.

Attribute-6 (A-6): Friction-recovery (%) (larger-is-better): It is calculated as:

\[
\text{Friction-recovery} = \frac{\mu_p}{\mu_{\text{r}}} \times 100 \quad (5)
\]
where $\mu_R$ is the highest $\mu$ value recorded during two recovery runs.

Attribute-7 (A-7): Wear (smaller-is-better): It is composite weight loss and computed as the difference of sample weight, before and after the test.

2.3. Ranking methodology

The systematic working of the hybrid CRITIC-MEW decision-making methodology is given in Fig. 2. The systematic can be divided into various phases, namely: Alternatives, attributes and decision matrix (Phase 1), CRITIC method (Phase 2) and MEW method (Phase 3).

2.3.1. Phase 1: alternatives, attributes and decision matrix

In the beginning a decision matrix was formulated after identifying potential alternatives and attributes. For $p$ ($p_i, i = 1, 2, \ldots, M$) alternative and $q$ ($q_j, j = 1, 2, \ldots, N$) attributes, a decision matrix of $p \times q$ order can be formulated as:

$$
D_{p \times q} = 
\begin{pmatrix}
\Delta_{11} & \Delta_{12} & \ldots & \Delta_{1j} & \ldots & \Delta_{1N} \\
\Delta_{21} & \Delta_{22} & \ldots & \Delta_{2j} & \ldots & \Delta_{2N} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\Delta_{i1} & \Delta_{i2} & \ldots & \Delta_{ij} & \ldots & \Delta_{iN} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\Delta_{M1} & \Delta_{M2} & \ldots & \Delta_{Mj} & \ldots & \Delta_{MN}
\end{pmatrix}
$$

where $\Delta_{ij}$ denotes $i^{th}$ alternative value with respect to $j^{th}$ attribute.

2.3.2. Phase 2: CRITIC method for weight calculation

The CRITIC method was proposed by Diakoulaki et al. [45], where standard deviation approach was used for determining attributes weight. The CRITIC method’s various steps are data normalization, correlation coefficient calculation, standard deviation calculation, index value generation, and weight calculation. The decision matrix was normalized according to attribute implication as presented in the following equations.
After normalization, the correlation coefficient ($\phi_{jk}$) among two attributes ($j$th and $k$th) is determined as:

$$\phi_{jk} = \frac{\sum_{i=1}^{M} (x_{ij} - \overline{x}_j) (x_{ik} - \overline{x}_k)}{\sqrt{\sum_{i=1}^{M} (x_{ij} - \overline{x}_j)^2 \sum_{i=1}^{M} (x_{ik} - \overline{x}_k)^2}}$$

(8)

where $\overline{x}_j$ and $\overline{x}_k$ are the mean of $j$th and $k$th attributes. The $\overline{x}_j$ is determined using following equation. Similarly, $\overline{x}_k$ is determined by replacing j with k.

$$\overline{x}_j = \frac{1}{N} \sum_{i=1}^{N} x_{ij}; \quad i = 1, \ldots, M$$

(9)

Thereafter, standard deviation ($\sigma_j$) of each attribute is estimated as:

$$\sigma_j = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_{ij} - \overline{x}_j)^2}; \quad i = 1, \ldots, M$$

(10)

Then, the index value ($\omega_j$) is determined using following equation.

$$\omega_j = \alpha \sum_{j=1}^{N} (1 - \phi_{jk}); \quad j = 1, \ldots, N$$

(11)

Finally the weights of attributes are determined as:

$$\omega_j = \frac{\omega_j}{\sum_{j=1}^{N} \omega_j}; \quad j = 1, \ldots, N$$

(12)

### 2.3.3. Phase 3: multiplicative exponent weighting (MEW) method

The MEW method is used widely for optimizing various decision making problems due to its simplicity [40]. It consists of the following steps:

**Step I:** For making attributes comparable the decision matrix entities were normalized using desired preference of beneficial and non-beneficial attributes as:

$$n_{ij} = \frac{d_{ij} - d_{ij}^{\min}}{d_{ij}^{\max} - d_{ij}^{\min}}, \text{ if } j \text{ is larger – is – better attribute and}$$

$$n_{ij} = \frac{d_{ij}^{\max} - d_{ij}}{d_{ij}^{\max} - d_{ij}^{\min}}, \text{ if } j \text{ is smaller – is – better attribute}$$

(13)

**Step II:** In this step weighted normalized decision matrix was obtained using following equation.

$$c_{ij} = (n_{ij})^\gamma$$

(14)

**Step III:** The score ($\Omega_i$) of each alternative is determined using product of weighted values as:

$$\Omega_i = \prod_{j=1}^{N} c_{ij}$$

(15)

The alternative with largest $\Omega_i$ is recommended as the optimal candidate.

### 3. Results and discussion

#### 3.1. Fade-recovery performance of the investigated composites

The friction performance of the manufactured composites during four fade-recovery runs is depicted in Fig. 3. During the fade-I run (i.e., a temperature range of 93–289 °C) of hemp fiber (i.e., FC1/FC2/FC3/FC4) and composites with ≥15 wt.% ramie fiber (i.e., FC7 and FC8), the $\mu$ value increased up to 149 °C. Conversely, some improvement in $\mu$ for ≤10 wt.% ramie fiber (i.e., FC5 and FC6) was observed to increase up to 177 °C. The $\mu$ values of 0.565 ± 0.015 for FC1/FC2/FC3/FC4/FC7/FC8 composites were obtained at ~149 °C and 0.585 ± 0.004 was registered for FC5/FC6 composites at ~177 °C, respectively. With further increase in temperature, the $\mu$ started decreasing and attained the lowest value at 289 °C. On the other hand, the $\mu$ starts decreasing from the beginning of the fade-I run, i.e., 93 °C for pineapple fiber-reinforced composites (i.e., FC9/FC10/FC11/FC12). This decrease was gradual for ≤15 wt.% hemp (FC1/FC2/FC3) and pineapple (FC9/FC10/FC11) fibre-reinforced composites.

A significant decline in $\mu$ was observed for ≥10 wt.% ramie (FC5/FC7/FC8), 20 wt.% hemp (FC4/FC5) and pineapple (FC12) fiber-reinforced composites. During the first recovery run, all investigated composites display an appreciable level of $\mu$. The $\mu$ increased with a decrease in temperature from 261 °C to 205 °C for ≤10 wt.% ramie fiber (i.e., FC5/FC6) based composites. Whereas, for other composites, the $\mu$ increased up to 149 °C and decreased until the recovery-I run was completed. During the recovery-I run, the least and most noteworthy $\mu$ estimations of 0.435 and 0.581 were enrolled for FC12 composite with 20 wt.% pineapple fiber. During the fade-II run, the investigated composites $\mu$ was impacted by the kind and weight fraction of natural fibers. The $\mu$ for all composites starts increasing at the beginning of the fade-II run. After attaining a peak at a certain temperature, the $\mu$ starts decreasing with increased temperature. The $\mu$ peaking temperature has remained formulation-dependent and shifted towards lower temperature with expanded fiber concentration. The composite with 5 wt.% hemp fiber (i.e., FC1) showed the largest $\mu$ value (0.570) at 261 °C and decreased slowly after that to 0.512 at the end of the fade-II run. For composites with ≥10 wt.% hemp fiber (i.e., FC2/FC3/FC4), a build-up in $\mu$ was observed until 177 °C with a continuous decay after that. For FC5/FC6 composites (having 10 wt.% ramie fiber), the largest $\mu$ values (0.597 ± 0.009) were registered at 261 °C (0.57) and observed to decrease gradually after that. With ramie fiber addition to 15–20 wt.% (i.e. FC7/FC8) largest $\mu$ values (0.548 ± 0.011) were registered at 233 °C. Similarly, for FC9 composite (having 5 wt.% pineapple fiber), the largest $\mu$ (0.576) was registered at 289 °C. With the further addition of 10–20 wt.% pineapple fiber (i.e., FC10/FC11/FC12), the $\mu$ peaking of the composites was shifted towards lower temperature (~177 °C). After completing the fade-II run, cooling was initiated. The $\mu$ values were recorded from 317 °C to 93 °C.
at an interval of 56 °C during the recovery-II run. Interestingly, for 5–10 wt.% hemp and ramie fiber (i.e., FC1/FC2/FC5/FC6) and 5–20 wt.% pineapple fiber (i.e., FC9/FC10/FC11/FC12) based composites, an increase in μ values was observed as temperature decreases from 317 °C to 261 °C and decreased after that until the completion of the recovery-II run, i.e., 93 °C. For 15–20 wt.% hemp (i.e., FC3/FC4) and ramie fiber-based composites (i.e., FC7/FC8), the highest μ values were observed at ~149 °C and ~205 °C, respectively. The lowest (0.462) and highest (0.609) μ were recorded for FC4 and FC8 composites.

3.2. Attributes results

The fade-recovery results are further analyzed in terms of performance attributes, as discussed in Section 2. The selected attributes’ results are listed in Table 3 and depicted in Figs. 4–7.

3.2.1. μP and friction fluctuations response

The μP (A-1) and friction fluctuations (A-2) results of the investigated composites are presented in Fig. 4. The μP values remain highest for 5 wt.% natural fiber-based composites and decrease with increased fiber amount. The smallest (0.501) and largest (0.548) values of μP were recorded for 20 wt.% ramie fiber (i.e. FC8) and 5 wt.% pineapple fiber (i.e. FC9) based composites respectively. When the composite contains 5–10 wt.% fiber content, the μP value remained between 0.540 and 0.548. In recent years, similar investigations

![Fig. 4 – Variation of A-1 (μP) and A-2 (friction fluctuations) with composition.](image)

![Fig. 5 – Variation of A-3 (friction stability) and A-4 (friction variability) with composition.](image)

![Fig. 6 – Variation of A-5 (friction-fade (%)) and A-6 (friction-recovery (%)) with composition.](image)
concerning the friction performance of natural fiber-based composites have been performed and well-described in the literature. Ma et al. [36] have reported the highest friction performance for 6 wt.% corn stalk fibers added composites. Corresponding results for decreased friction performance, with increased mineral fiber content, were reported by Liu et al. [46]. It has been reported that friction coefficient is highest for 9 wt.% mineral fiber added composites and decreased with further addition of fiber.

However, by adding 15 wt.% fiber amount, the $\mu_p$ value decreases slightly to $0.535 \pm 0.003$ for hemp (i.e., FC3) and pineapple (i.e., FC11) fiber-based composite. This decrease in $\mu_p$ was considerable for 15 wt.% ramie fiber (i.e., FC7) based composite with 0.511 value of $\mu_p$. Further, the $\mu_p$ suffered a considerable drop as the fiber amount increased to 20 wt.%. This decline in $\mu_p$ magnitude may be ascribed to increased natural fiber concentration in phenolic resin that enhances the presence of organic ingredients on the sliding interface [25]. The degradation of organic ingredients with increased temperature enhances the generation of contact/friction film, resulting in the reduction of $\mu_p$ [25,30]. Similar results for reduced friction coefficient with increased organic fiber content were reported by Ahmadijokani et al. [47]. Ma et al. [48] fabricated friction composites reinforced with cow dung fibers (0–8 wt.%) and investigated their tribological properties. The highest improvement in friction performance was reached for composites with 4 wt.% of cow dung fibers, whereas beyond this limit useful properties deteriorate as reported. Further, friction fluctuations (Fig. 4) remain lowest for 5 wt.% natural fiber-based composites and are found to increase with increased fiber amount. Comprehensively, composites having a higher performance coefficient of friction exhibit lower frictional fluctuations. The friction fluctuation value remained in the range of $0.210 \pm 0.031$ for composites having 5 wt.% natural fiber. However, by adding 20 wt.% of natural fiber, the composites’ friction fluctuation increased considerably and remained in between $0.331 \pm 0.035$. The composite FC5 is containing 5 wt.% ramie fiber display the slightest friction fluctuation (0.178), while for 20 wt.% pineapple fiber (i.e., FC12) based composite, the friction fluctuation (0.366) remains highest. The observed ascending trend of friction fluctuation values with increased organic fiber content is in good agreement with the literature [49]. Similar results for increased friction fluctuation with increased banana fiber content was reported by Zhen-Yu et al. [50]. Authors manufactured friction composites with banana fiber (0–20 wt.%) and evaluated the tribological properties. They reported that friction fluctuation remains lowest for ≤10 wt.% banana fiber added composites and increased significantly with further addition of fiber.

3.2.2. Friction stability-variability response
The friction stability (A-3) and friction variability (A-4) aspects of the investigated composites are depicted in Fig. 5. For efficient braking response, higher friction stability and lower friction variability are the desired attributes [33]. The friction variability was found to increase, whereas friction stability decreased with high fiber content. The most increased friction stability ($\geq 0.91$) and lowest friction variability ($0.385 \pm 0.055$) was recorded for 5 wt.% fiber-based composites. Further, a slight decrease in friction stability ($0.85 \pm 0.02$) and an abrupt increase in friction variability ($0.635 \pm 0.065$) was noted as the fiber content increased to 20 wt.%. This increase in friction variability may arise due to the improper distribution/mixing of increased fiber concentration, which brings structural inhomogeneities in the composites, resulting in reduced friction stability with increased variability. Similar observations with increased organic fiber content for decreased friction stability and increased friction variability were reported by Kumar et al. [49] and Patnaik et al. [51].

3.2.3. Friction-recovery (%)and friction-fade (%) response
The friction-recovery (%) and friction-fade (%) response of the tested composites is presented in Fig. 6. Higher friction-recovery (%) and lower friction-fade (%) are the desired attributes for efficient braking. It is observed that friction-fade (%) remained lower (−24.40 ± 2.28%) for FC5/FC6 composites (having ≤10 wt.% ramie fiber). Nevertheless, for composites FC4, FC8, and FC12 with higher natural fiber (20 wt.%), the friction-fade (%) was found to increase and remain between −45.46 ± 7.30%. It can be noted that the inclusion of higher natural fiber resulted in increased friction-fade (%) while lower natural fiber leads to a reduced level of friction-fade (%). This increase in friction-fade (%) might be credited to the expanded organic content (natural fiber and phenolic resin) in the composites. The pyrolysis of organic constituents results in the generation of contact film at the tribo-interface, decreasing the frictional force and induces fade, as reported by various researchers [25,30,52].

Nonetheless, the friction-recovery (%) for all alternatives remained more than 100% and observed to increase with increased natural fiber content. The extent of friction-recovery (%) remained in the range of −112 ± 5% for ≥15 wt.% natural fiber-based composites. In contrast, it remains in the range of 117.84 ± 5% for 20 wt.% natural fiber-based composites i.e., FC4, FC8, and FC12. The improper distribution/mixing of increased fiber concentration brings structural irregularities in the composites and hence resulted in the formation of wear particles/debris during braking. During the recovery run, these wear debris was act as hard abrasives particles and increase the $\mu$ value via a third body rolling mechanism. Overall the friction-fade (%) and friction-...
recovery (%) of the investigated composites increased with increased natural fiber content. The composite FC5 (containing 5 wt.% ramie fiber) shows the smallest value for friction-fade (22.12%), while the largest value for friction-recovery (121.56%) was exhibited by composite FC8 containing 20 wt.% nylon fiber. The observed trends were consistent with the literature. Satapathy and Bijwe [53] reported that the recovery performance of cellulose fiber-reinforced friction composites remains highest in comparison to aramid, polyacrylonitrile, and carbon-based friction composites. Ma and co-workers [30] prepared phenolic resin-based composite with corn stalk fibers (0–8 wt.%) and investigated their tribological properties. As per [30], the fade performance was significantly enhanced with the addition of 6 wt.% corn stalk fibers. Similar observations were made for rattan fiber (0–10 wt.%) based friction composites by Ma et al. [22]. According to this work, the lowest fade and highest recovery were registered in 5 wt.% rattan fiber added friction composites.

### 3.2.4. Wear performance of composites

The influence of natural fibers on the wear performance (A-7) of the investigated composites is presented in Fig. 7. The wear of the composites was found to increase with the addition of increased natural fiber concentration. The wear was remained lower (1.22 ± 0.14 g) for ≤ 10 wt.% natural fiber-based composites and raised for ≥ 15 wt.% natural fiber-based composites and remained ~1.62 ± 0.18 g. The lower wear for ≤ 10 wt.% natural fiber-based composites was credited to the formation of contact film and its adherence to the tribo-couple during braking.

The wear (1.08 g) remains lowest for 5 wt.% hemp fiber reinforced composite, i.e., FC1, where it increases by ~66% to 1.8 g for the composite with 20 wt.% pineapple fiber, i.e., FC12, and remained highest overall. The higher wear for increased natural fiber-based composites was mainly ascribed to the thermal degradation and uneven distribution of the natural fibers. The natural fiber starts degrading above 200 °C temperature, causing the surface damage and wear debris detachment easier. Moreover, increased fiber amount resulting in agglomeration/non-uniform distribution in composites made them easily detachable during braking and increased wear [25,41–43]. A similar trend was reported by Maleque and Atiqah [28] for coir (0–20 vol.%) fiber-reinforced friction composites. Authors concluded that wear remains lowest for 5 vol.% coir added friction composites and increased with further addition of coir fiber. While studying the influence of corn stalk and cow dung fibers (0–8 wt.%), Ma et al. [30,48] reported that wear remains lowest for 6 wt.% corn stalk and cow dung fibers added friction composites. Zhen-Yu and co-workers [50] manufactured phenolic resin-based friction composite with banana fibers (0–20 wt.%) and investigated their tribological properties. The author concluded that wear resistance remains highest for lower 5 wt.% added composites and decreased with further addition of fibers.

It is evident from Table 3 and Figs. 4–7 that the type and amount of natural fibers have a considerable impact on the performance attributes. The μf and friction-stability of FC9 composite were superior among all alternatives, but it exhibits the second-lowest friction-recovery value (107.66%). The alternative FC5 exhibits lowest friction-fade (22.12%) with least friction-variability (0.33) and friction fluctuations (0.178). The lowest wear (1.08 g) and the highest value of friction-stability (0.93) were recorded for the FC5 composite, but the same record the lowest friction-recovery (107.54%). However, the lowest friction-fade (52.78%), friction-variability (0.7), and highest wear (1.8 g) were exhibited by the FC12 alternative with 20 wt.% pineapple fiber. Whereas, highest friction-recovery (121.56%) with the lowest μf (0.501) and friction-stability (0.82) as exhibited by the FC8 alternative with 20 wt.% ramie fiber. The results uncover no particular alternative that shows the best solution by considering all attributes simultaneously. Hence, it is difficult to suggest an alternative for which the composite will deliver the highest tribo-performance. Therefore, the hybrid CRITIC-WE technique is utilized to rank these composites.

### Table 4 – Attributes weight determined using CRITIC method.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
<th>A-5</th>
<th>A-6</th>
<th>A-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ</td>
<td>0.3309</td>
<td>0.2782</td>
<td>0.3152</td>
<td>0.2891</td>
<td>0.2645</td>
<td>0.3132</td>
<td>0.3391</td>
</tr>
<tr>
<td>ψ</td>
<td>1.1171</td>
<td>0.6194</td>
<td>0.9838</td>
<td>0.6252</td>
<td>0.6922</td>
<td>3.0022</td>
<td>0.8147</td>
</tr>
<tr>
<td>ω</td>
<td>0.1422</td>
<td>0.0789</td>
<td>0.1253</td>
<td>0.0796</td>
<td>0.6081</td>
<td>0.3822</td>
<td>0.1037</td>
</tr>
</tbody>
</table>

### Table 5 – Decision matrix normalization.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
<th>A-5</th>
<th>A-6</th>
<th>A-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC1</td>
<td>0.9927</td>
<td>1.0000</td>
<td>0.7293</td>
<td>0.8641</td>
<td>0.8847</td>
<td>1.0000</td>
<td>0.8684</td>
</tr>
<tr>
<td>FC2</td>
<td>0.9854</td>
<td>0.9892</td>
<td>0.6564</td>
<td>0.7773</td>
<td>0.8942</td>
<td>0.8926</td>
<td>0.7857</td>
</tr>
<tr>
<td>FC3</td>
<td>0.9078</td>
<td>0.9677</td>
<td>0.5551</td>
<td>0.6568</td>
<td>0.9139</td>
<td>0.7448</td>
<td>0.6471</td>
</tr>
<tr>
<td>FC4</td>
<td>0.9398</td>
<td>0.9355</td>
<td>0.5298</td>
<td>0.6034</td>
<td>0.9504</td>
<td>0.6391</td>
<td>0.5789</td>
</tr>
<tr>
<td>FC5</td>
<td>0.9982</td>
<td>0.9785</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.8978</td>
<td>0.9310</td>
<td>1.0000</td>
</tr>
<tr>
<td>FC6</td>
<td>0.9854</td>
<td>0.9570</td>
<td>0.8294</td>
<td>0.8517</td>
<td>0.9217</td>
<td>0.8060</td>
<td>0.8462</td>
</tr>
<tr>
<td>FC7</td>
<td>0.9325</td>
<td>0.9140</td>
<td>0.6315</td>
<td>0.6617</td>
<td>0.9675</td>
<td>0.7105</td>
<td>0.6226</td>
</tr>
<tr>
<td>FC8</td>
<td>0.9142</td>
<td>0.8817</td>
<td>0.5803</td>
<td>0.5953</td>
<td>1.0000</td>
<td>0.6034</td>
<td>0.5500</td>
</tr>
<tr>
<td>FC9</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.6092</td>
<td>0.7386</td>
<td>0.8857</td>
<td>0.8852</td>
<td>0.7500</td>
</tr>
<tr>
<td>FC10</td>
<td>0.9854</td>
<td>0.9677</td>
<td>0.5688</td>
<td>0.6642</td>
<td>0.8958</td>
<td>0.7941</td>
<td>0.6600</td>
</tr>
<tr>
<td>FC11</td>
<td>0.9818</td>
<td>0.9462</td>
<td>0.5000</td>
<td>0.5779</td>
<td>0.8960</td>
<td>0.7013</td>
<td>0.5789</td>
</tr>
<tr>
<td>FC12</td>
<td>0.9507</td>
<td>0.9140</td>
<td>0.4191</td>
<td>0.4863</td>
<td>0.9174</td>
<td>0.6000</td>
<td>0.4714</td>
</tr>
</tbody>
</table>
3.3. Ranking of the friction composites

The experimental results were arranged in a decision matrix using Eq. (6) and presented in Table 3. The attribute weights were computed with the help of the CRITIC method. First of all, the decision matrix was normalized using Eq. (7), and the selected attribute weights were calculated by applying Eqs. (8)–(12). The results of the CRITIC method are presented in Table 4. After the attribute weight determination, the MEW method was used for ranking the alternative. For this, the decision matrix was normalized by applying Eq. (13) and presented in Table 5.

Further, the weighted normalized decision matrix was determined using Eq. (14) and presented in Table 6. Thereafter, the preference score ($\Omega_i$) of the alternatives with respect to selected attributes was determined by using Eq. (15) and presented in Table 6. Based on $\Omega_i$, the alternative ranking presented in Table 6 and has the flowing structure: FC5 > FC12 > FC6 > FC2 > FC9 > FC7 > FC10 > FC3 > FC8 > FC4 > FC11 > FC12. The highest score of 0.9542 was exhibited by alternative/composite FC5, while the score for the alternative/composite FC12 was found to remain lowest with a value of 0.7453. Therefore, the alternative/composite FC5 (containing 5 wt.% ramie fiber) is considered the best option to maximize the overall tribological performance for the automotive braking application. Simultaneously, the alternative/composite FC12 (containing 20 wt.% pineapple fiber) is adjudged the least preferred candidate for the given application.

4. Conclusions

In this work, a multicriteria decision-making technique was applied to the problem of choosing an optimal brake friction formulation satisfying a maximum number of preset performance criteria. Twelve composites containing various reinforcements (hemp, ramie, and pineapple) of 5, 10, 15, and 20 wt.% were manufactured and analyzed for tribological properties. For selecting the best composition, seven performance attributes, namely friction-fade (%), friction performance, friction-recovery (%), friction-variability, friction fluctuations, friction-stability, and wear, were selected. The friction performance and friction stability of the composites decrease while friction-fade (%), wear, friction fluctuations, friction-recovery (%), and friction-variability increase with increased fiber content. Since no single composite alternative could satisfy all the desired performance, the hybrid CRITIC-MEW approach was used to identify the final ranking. The CRITIC-MEW assessment showed that the composite containing 5 wt.% ramie fiber displayed the desired tribological performance. Hence, the hybrid CRITIC-MEW approach represents an effective optimization tool for selecting brake friction formulation when the performance attributes on a set of composites are composition-dependent and show no definite pattern in tribological performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES


