

## Optimisation and Performance Evaluation of Brake Pad from *Bauhinia Thoningii* Pods

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### Abstract

#### Keywords:

Wear, Brake pad, Hardness, Optimisation, and *Bauhinia Thoningii* pods.

The toxicity of asbestos, a traditional friction material in brake pads, has driven the search for sustainable alternatives. This study explores the use of *Bauhinia thoningii* pods (BTP) as reinforcement in non-asbestos organic (NAO) brake pad composites. The pods were chemically treated with 5% NaOH and H<sub>2</sub>O<sub>2</sub>, sieved into three grain sizes, and fabricated via cold pressing and oven curing. Using Design Expert™ software, 23 runs of formulation constituents (*Bauhinia*, alumina, and calcium carbonate) with ranges of sieve size using categories factor with three levels and 17 runs of process parameters such as compaction pressure (CP), Holding time (HT), curing temperature (CT), and curing time (Ct) were optimised for Physico-mechanical and tribological properties (density, hardness, and coefficient of friction) of BTP brake pads. The properties of the optimised BTP brake pad were evaluated and compared with the commercial brake pad (CBP) AUTO-BOSS D2217. The results revealed that finer BTP grain size of 20-40  $\mu\text{m}$  and lower pod content (15.45%) improved hardness (323.8 Hv) and density (1.79 g/cm<sup>3</sup>), while higher alumina content (14.54%) enhanced frictional stability. Increased compaction pressure and curing temperature improved hardness and density, whereas extended curing time stabilised the coefficient of friction (COF) and enhanced wear resistance. The optimised BTP brake pad at 200 kN compaction Pressure, 5 min holding time, 100 °C curing temperature and 2 min curing time showed higher density (2.72 g/cm<sup>3</sup>), hardness (284.86 HV), wear resistance (10.12 mm/mm<sup>3</sup>), with lower COF (0.437) than CBP density (1.52 g/cm<sup>3</sup>), hardness (206.94 HV), wear resistance (4.17 mm/mm<sup>3</sup>), and COF (0.3535) respectively, demonstrating improved mechanical and tribological properties.

### 1. Introduction

The transportation sector is a major contributor to global carbon emissions and environmental pollution, with road vehicles accounting for nearly 70% of transport-related CO<sub>2</sub> output (Tsigidinos, 2025; Gu et al., 2024). Beyond fuel combustion, vehicle parts such as brake pads release particulate matter and potentially hazardous compounds during operation, raising concerns about both environmental and public health impacts. Brake pads are critical safety components, converting kinetic energy into heat through friction against the rotor. Their material evolution has progressed from rudimentary wooden blocks and leather linings to asbestos-based composites, semi-metallic pads, and more recently, ceramic and carbon–ceramic systems.

Asbestos, once widely adopted for its thermal stability and durability, has been banned in many countries due to its carcinogenic nature and association with severe respiratory illnesses (Gunjal and Chougule, 2022; Zephaniah and Aremu, 2019). This regulatory shift has prompted extensive research into eco-friendly alternatives, particularly those derived from agricultural and forestry residues. Natural fillers such as palm kernel shell (Popoola et al., 2021), coconut shell (Popoola et al., 2021), seashell powder (Adekunle et al., 2023), rice husk (Nogueira et al., 2022), jute fibre (Kumar et al., 2021), and flax fibre (Jahan et al., 2022) have demonstrated promise in brake pad composites, offering renewable sourcing and reduced toxicity. However, challenges remain in achieving the mechanical strength, wear resistance, and thermal stability required for commercial applications.

*Bauhinia thonningii* (also known as camel foot) is a woody leguminous tree native to sub-Saharan Africa that produces fibrous pods (Gebre et al., 2022). Despite its abundance and agroforestry value, the *Bauhinia thonningii* has been underexplored in friction material development. Furthermore, while prior studies have primarily focused on formulation variables or process parameters in isolation, with limited attention to sequential optimisation, this approach first optimises formulation variables, followed by process parameters such as compaction pressure, curing temperature, and curing time, which critically influence composite performance. This sequential optimisation strategy offers a pathway to balanced mechanical and tribological properties, ensuring that natural fibre-based brake pads achieve both durability and reliability.

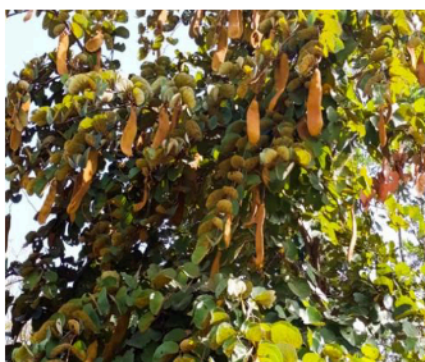
This study, therefore, investigates the development of non-asbestos organic (NAO) brake pads using the *Bauhinia thonningii* pods as reinforcement.

## 2.0 Materials and Method

### 2.1 Materials

This research employs sequential optimisation to refine both formulation design and processing conditions, evaluating physico-mechanical and tribological properties, including density, hardness, coefficient of friction, and wear resistance. Comparative analysis with a commercial brake pad provides insight into the feasibility of BTP as a sustainable friction material.

The *Bauhinia thonningii* pods (BTPs) shown in Figure 1 (a) and (b) were collected from the University of Ilorin Forest/bushes and other chemical constituents such as Calcium carbonate (98%, MCR-22405), Alumina (90% purity, MCR-16344-01), Magnesium oxide (98%, MCR-17839), Graphite (98%, MCR-26103), and Epoxy resin with hardener were obtained from the Mich-Mikedenson chemical shop, Post-office, Ilorin.



(a)

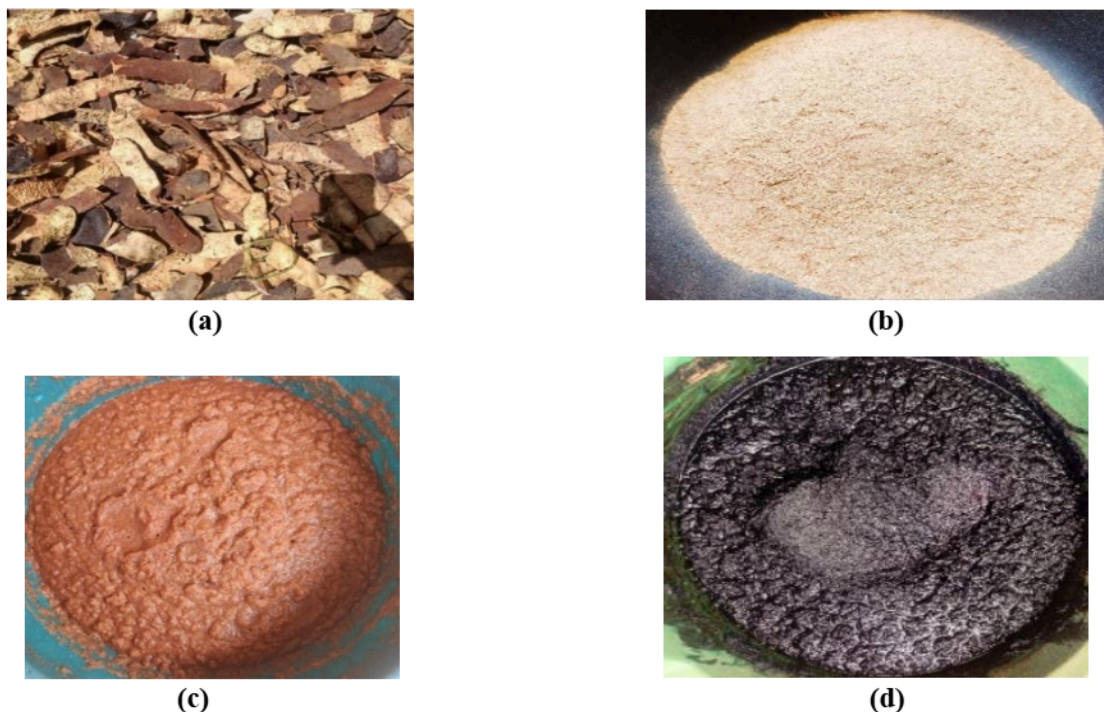


(b)

**Figure 1:** (a) *Bauhinia Thonningii* Tree, (b) Mature *Bauhinia Thonningii* pods

## 2.2 Pod Processing and Fibre Pre-treatment

The pods were soaked in water for 2–3 days to facilitate the separation of the outer shell from the pulp. The shells were sun-dried for 5 days, pulverised as shown in Figures 2 (a) and (b) using 5 horse power hammer mill. The pulverised samples subjected to sequential chemical pre-treatment shown in Figure 2 (c) with 5% NaOH followed by 5% H<sub>2</sub>O<sub>2</sub>, rinsing to neutral pH after each step. Upon completion of both treatments, the fibres were oven-dried as shown in Figure 2 (d) at 80 °C to constant weight using a thermostat oven (MODEL DHG-9053A). The resulting powder was sieved into three fractions (20–40 µm, 40–72 µm, and 100–120 µm) using Sieves (BSS20) and stored in sealed polythene bags for subsequent use.



**Figure 2:** Pod processing and Fibre Treatment (a) Dried *Bauhinia thonningii* pods (b) Pulverised *Bauhinia thonningii* pods (c) Treated BTP Slurry (d) Oven Dried Treated BTP Slurry

## 2.3 Experimental Design and Optimisation

The optimisation was carried out using a sequential approach, beginning with formulation optimisation and followed by process parameter optimisation on the Design Expert 13. The formulation optimisation was designed utilising the optimal mixture design formulation constituents (*Bauhinia*, alumina, and calcium carbonate) with sieve size ranges using categories factor with three levels (20–40, 40–72 and 100–120 µm). Components were varied within ranges shown in Table 1: *Bauhinia* (14–30%), alumina (6–16%), graphite (10%), calcium carbonate (12–24%), MgO (6%), epoxy and hardener (30%, 2:1 ratio) according to Achebe et al., (2019); Ikpambese et al. (2018); Egeonu et al. (2015). A total of 23 formulations were tested. The experimental data were analysed using a reduced Quadratic Mixture × Main Effects Scheffe model, which accounts for the linear contributions of mixture components and the main effects of process variables. The optimisation was conducted to maximise density and coefficient of friction (COF), while maintaining a hardness of 200–220 HV. The process parameter optimisation shown in Table 2 was varied across the following levels: compaction pressure (40–120–200 kN), holding time (5–12.5–20min), curing temperature (100–200–300 °C), and curing time (1–2–3hr) according to Achebe et al., (2019) and Egeonu et al. (2015). A total of 17 samples were tested. The samples were produced using the optimal formulation from the

formulation optimisation experiment, thoroughly mixed (~7 min), and processed according to the parameters for each run. The density, hardness, and COF were analysed using a quadratic model.

**Table 1:** Formulation Parameters Optimisation of BTP Brake Pads

| Runs | Bauhinia | Alumina | CaCO <sub>3</sub> | Graphite | MgO | Binder |
|------|----------|---------|-------------------|----------|-----|--------|
| 1    | 23.4     | 16.0    | 14.6              | 10       | 6   | 30     |
| 2    | 15.2     | 14.8    | 24.0              | 10       | 6   | 30     |
| 3    | 22.3     | 16.0    | 15.7              | 10       | 6   | 30     |
| 4    | 30.0     | 12.0    | 12.0              | 10       | 6   | 30     |
| 5    | 26.0     | 16.0    | 12.0              | 10       | 6   | 30     |
| 6    | 23.5     | 6.6     | 24.0              | 10       | 6   | 30     |
| 7    | 23.4     | 11.6    | 19.0              | 10       | 6   | 30     |
| 8    | 30.0     | 6.0     | 18.0              | 10       | 6   | 30     |
| 9    | 14.9     | 15.4    | 23.7              | 10       | 6   | 30     |
| 10   | 23.4     | 11.0    | 19.6              | 10       | 6   | 30     |
| 11   | 19.1     | 10.9    | 24.0              | 10       | 6   | 30     |
| 12   | 26.6     | 11.5    | 15.9              | 10       | 6   | 30     |
| 13   | 30.0     | 6.0     | 18.0              | 10       | 6   | 30     |
| 14   | 22.9     | 11.4    | 19.7              | 10       | 6   | 30     |
| 15   | 22.6     | 1.4     | 24.0              | 10       | 6   | 30     |
| 16   | 14.5     | 15.5    | 24.0              | 10       | 6   | 30     |
| 17   | 18.9     | 16.0    | 19.1              | 10       | 6   | 30     |
| 18   | 29.7     | 12.3    | 12.0              | 10       | 6   | 30     |
| 19   | 23.5     | 6.6     | 24.0              | 10       | 6   | 30     |
| 20   | 30.0     | 6.1     | 17.9              | 10       | 6   | 30     |
| 21   | 23.1     | 16.0    | 14.9              | 10       | 6   | 30     |
| 22   | 30.0     | 12.0    | 12.0              | 10       | 6   | 30     |
| 23   | 18.9     | 16.0    | 19.1              | 10       | 6   | 30     |

**Table 2:** Process Parameters Optimisation runs of BTP Brake Pads

| Runs | Compaction Pressure (kN) | Holding Time (min) | Curing Temp (°C) | Curing Time (hr) |
|------|--------------------------|--------------------|------------------|------------------|
| 1    | 120                      | 12.5               | 200              | 2                |
| 2    | 120                      | 12.5               | 100              | 3                |
| 3    | 120                      | 12.5               | 200              | 2                |
| 4    | 40                       | 20                 | 200              | 1                |
| 5    | 200                      | 5                  | 100              | 2                |
| 6    | 200                      | 12.5               | 300              | 1                |
| 7    | 200                      | 5                  | 100              | 2                |
| 8    | 40                       | 5                  | 200              | 3                |
| 9    | 120                      | 5                  | 200              | 1                |
| 10   | 40                       | 12.5               | 300              | 3                |
| 11   | 200                      | 5                  | 300              | 3                |
| 12   | 200                      | 20                 | 200              | 3                |
| 13   | 40                       | 12.5               | 300              | 1                |
| 14   | 40                       | 12.5               | 100              | 1                |
| 15   | 40                       | 20                 | 100              | 2                |
| 16   | 120                      | 20                 | 300              | 2                |
| 17   | 200                      | 20                 | 100              | 1                |

## 2.4 Brake Pad Production

Calcium carbonate was used as a filler, alumina as an abrasive (Ezekiel *et al.*, 2019; Ramanathan *et al.*, 2017; Sutikno *et al.*, 2018; Ünalı and Kuş, 2018), magnesium oxide (MgO) as an additive to enhance the thermal resistance of the resin (Ge *et al.*, 2020; Hornak *et al.*, 2018; Sutikno *et al.*, 2018), and graphite as a lubricant (Ramanathan *et al.*, 2017). Epoxy resin, combined with a hardener, served as the binder (Adekunle *et al.*, 2023). The Epoxy resin and hardener (2:1 ratio) were first mixed separately, then combined with the dry powders to obtain a homogeneous, low-moisture mixture capable of retaining shape under compression. The binder content was determined through preliminary trials and fixed at 30 wt% to achieve this mixture quality. The mixture was transferred into a steel mould and compressed using a hydraulic press. For formulation optimisation, samples were compressed at 40 kN for 10 min and cured at 150 °C for 60 min. For process optimisation, compaction pressure, curing temperature, curing time, and holding time were varied according to Table 2. After compressing, samples were ejected, air-dried for 24 h, and oven-cured.

## 2.5 Determination of Physical and Mechanical Properties

### 2.5.1 Density measurement

Density was determined using Archimedes' principle, based on the mass in air ( $m$ , g) and displaced water volume ( $V$ , cm<sup>3</sup>), without temperature correction. The density is determined using Equation (1) below.

$$\text{Density } (\rho) = \frac{m}{V} \text{ [g/cm}^3\text{]} \quad (1)$$

where  $m$  is the mass of the sample in air and  $V$  is the displaced water volume.

### 2.5.2 Vickers hardness

The samples were polished using P60 and P220 sandpaper before testing. Hardness was measured with a Vickers hardness testing machine using five indentations under a 10N load, and a 15s dwell time. The diagonal lengths were measured with a calibrated optical microscope, and hardness was calculated according to ASTM E384-17 and ISO 6507-1 using Equation (2);

$$VHN(HV) = \frac{1.8544F}{d^2} \text{ [kgf/mm}^2\text{]} \quad (2)$$

where  $F$  is the applied load (kgf),  $d$  is the average diagonal length (mm), and 1.8544 is a geometric constant based on the indenter shape.

## 2.6 Determination of Tribological Properties

### 2.6.1 Coefficient of friction (COF)

The dynamic coefficient of friction (COF) was determined using a custom sliding setup comprising a steel plate, a graduated ruler for calibration, and a camera mounted on a stable stand. The steel plate was fixed to a rigid bench, whose inclination was checked to ensure a horizontal alignment. Before each trial, the plate surface was cleaned with a soft metal sponge to maintain consistent contact conditions. The ruler was aligned parallel to the sliding path for scale calibration, and the camera was positioned to record the sliding motion. Motion calibration was checked against it before each run. Test samples were uniformly sanded with P60 and P220 abrasive papers, marked for tracking, and launched across the steel plate. Motion was recorded at 1920 × 1080 pixels and 30 fps, manually tracked frame-by-frame, and analysed using the Fizziq motion tool, which generated velocity–time plots. The deceleration was obtained from the velocity–time curve according to Equation (3), and the dynamic COF was calculated using Equations (3) and (4) below:

$$a = \frac{(V_2 - V_1)}{(t_2 - t_1)} [\text{m/s}^2] \quad (3)$$

$$\mu_d = \frac{a}{g} \quad (4)$$

where  $V$  is velocity (m/s),  $t$  is time (s),  $a$  is deceleration,  $g$  is gravitational acceleration, and  $\mu_d$  is the dynamic COF.

### 2.6.2 Wear resistance test

Wear resistance of the material was evaluated using a pin-on-disc tribometer, a standard technique in Tribology for assessing sliding wear performance. In this method, the sample is brought into contact with a rotating disc under a controlled normal load of 10 N for a specified duration (5 s). During sliding, material is gradually removed due to frictional interaction between the contacting surfaces. The specific wear rate and wear resistance were calculated using Equations (5), (6), and (7):

$$\text{Volume loss } \Delta V = \frac{w}{\rho} \quad (5)$$

$$\text{Specific wear rate } W_s = \frac{\Delta V}{F \times S} \quad (6)$$

$$\text{Wear resistance } W_r = \frac{S}{V} \quad (7)$$

where  $\Delta V$  is volume loss ( $\text{mm}^3$ ),  $w$  is weight loss (g),  $\rho$  is density ( $\text{g/cm}^3$ ),  $F$  is applied load (N),  $S$  is sliding distance (m),  $W_s$  is specific wear rate ( $\text{mm}^3/\text{Nm}$ ), and  $W_r$  is wear resistance ( $\text{mm/mm}^3$ ).

## 3.0 RESULTS AND DISCUSSION

### 3.1 Experimental Results for Formulation and Process Parameters of BTP Brake Pad

The experimental results, using a custom mixture design, are shown in Table 3 to study the effects of Bauhinia, alumina, and calcium carbonate on brake pad properties. Results showed COF (0.2266–0.3471), hardness (135.60–329.64 HV), and density (0.90–1.85  $\text{g/cm}^3$ ), indicating strong compositional influence. Run 2 was predicted to be an optimal formulation, with balanced properties ( $\mu = 0.301$ , hardness = 329.64 HV, density = 1.85  $\text{g/cm}^3$ ), showing improved hardness over the CBP but slightly lower friction and density. Trade-offs were observed, as higher density did not always yield higher friction. Overall, optimized formulations enhanced wear resistance, load capacity, and durability, consistent with recent studies on hybrid filler performance (Kumar & Bijwe, 2013; Ramesh & Suresha, 2014; Singh *et al.*, 2015).

The Results in Table 4 show COF ranged from 0.2532–0.4900, hardness from 204.08–434.00 HV, and density from 1.53–2.73  $\text{g/cm}^3$ , indicating strong process sensitivity. Run 3 was identified as optimal, with  $\mu_d = 0.4900$  and density = 1.84  $\text{g/cm}^3$ , outperforming the CBP ( $\mu = 0.3535$ , density = 1.52  $\text{g/cm}^3$ ), though with slightly higher hardness trade-offs. This suggests improved frictional performance and structural stability. High compaction and curing conditions significantly enhanced densification and interfacial bonding. These trends agree with recent findings on process optimisation in brake materials (Demir, 2025; Ramesh & Suresha, 2014).

**Table 3:** The Response Results for Formulation Parameters Optimisation

| Runs | COF ( $\mu$ ) | Hardness (HV) | Density ( $\text{g/cm}^3$ ) |
|------|---------------|---------------|-----------------------------|
| 1    | 0.2832        | 265.64        | 0.90                        |
| 2    | 0.3011        | 323.64        | 1.81                        |
| 3    | 0.2422        | 189.84        | 1.06                        |
| 4    | 0.3333        | 182.88        | 0.96                        |
| 5    | 0.3145        | 213.32        | 1.34                        |
| 6    | 0.3004        | 198.84        | 0.99                        |
| 7    | 0.2749        | 266.66        | 1.01                        |
| 8    | 0.2729        | 176.06        | 1.21                        |
| 9    | 0.2596        | 205.34        | 1.24                        |
| 10   | 0.2859        | 141.34        | 1.21                        |
| 11   | 0.2835        | 165.18        | 1.28                        |
| 12   | 0.2986        | 143.92        | 1.03                        |
| 13   | 0.2266        | 168.68        | 1.00                        |
| 14   | 0.3093        | 170.08        | 1.07                        |
| 15   | 0.2538        | 220.14        | 1.09                        |
| 16   | 0.2906        | 281.84        | 1.21                        |
| 17   | 0.2480        | 248.74        | 1.21                        |
| 18   | 0.3319        | 254.28        | 0.99                        |
| 19   | 0.2956        | 135.60        | 1.00                        |
| 20   | 0.2576        | 194.48        | 1.00                        |
| 21   | 0.2677        | 183.30        | 1.03                        |
| 22   | 0.2597        | 203.06        | 1.01                        |
| 23   | 0.3471        | 240.78        | 1.27                        |

**Table 4:** The Response Results for Process Parameters Optimisation

| Runs | COF ( $\mu$ ) | Hardness (HV) | Density ( $\text{g/cm}^3$ ) |
|------|---------------|---------------|-----------------------------|
| 1    | 0.4735        | 351.33        | 1.72                        |
| 2    | 0.4527        | 304.84        | 2.04                        |
| 3    | 0.4900        | 254.84        | 1.84                        |
| 4    | 0.4209        | 321.50        | 1.78                        |
| 5    | 0.4295        | 283.81        | 2.71                        |
| 6    | 0.3125        | 377.96        | 2.12                        |
| 7    | 0.3637        | 278.08        | 2.73                        |
| 8    | 0.3387        | 361.10        | 1.66                        |
| 9    | 0.2825        | 245.90        | 1.80                        |
| 10   | 0.2807        | 318.08        | 1.53                        |
| 11   | 0.3220        | 311.64        | 1.62                        |
| 12   | 0.2532        | 249.98        | 1.62                        |
| 13   | 0.2858        | 240.08        | 1.90                        |

|    |        |        |      |
|----|--------|--------|------|
| 14 | 0.2973 | 301.82 | 1.55 |
| 15 | 0.2674 | 204.08 | 1.53 |
| 16 | 0.2638 | 434.00 | 1.96 |

| Runs | COF ( $\mu$ ) | Hardness (HV) | Density ( $\text{g/cm}^3$ ) |
|------|---------------|---------------|-----------------------------|
| 17   | 0.2919        | 323.10        | 1.83                        |

### 3.2 Effect and Interaction of Formulation and Process Parameters on COF of BTP Brake Pad

#### 3.2.1 Effect and interaction of formulation parameters on COF of BTP brake pad

The models in equation (8) revealed the effect and interaction of the formulation factors on the COF response of BTP brake pad.

$$\text{COF} = 1.199 \text{ Bauhinia} - 2.9584 \text{ Alumina} + 3.7537 \text{ CaCO}_3 + 12.7294 \text{ Bauhinia} * \text{Alumina} - 14.93576 \text{ Bauhinia} * \text{CaCO}_3 - 2.4907 \text{ Alumina} * \text{CaCO}_3 \quad (8)$$

The positive coefficients of Bauhinia (1.199) and  $\text{CaCO}_3$  (3.7537) shown in Equation (8) indicated that these constituents enhance COF. Natural fiber-based materials such as Bauhinia contribute to improved friction through the formation of stable contact plateaus and increased surface roughness, which enhances adhesion at the friction interface. Similarly,  $\text{CaCO}_3$  acts as a space filler that promotes the formation of friction films, improving contact stability and friction performance (Park et al., 2022). In contrast, the negative coefficient of alumina ( $\text{Al}_2\text{O}_3$ ) (−2.9584) suggests a reduction in COF at higher concentrations. This is consistent with findings that hard ceramic particles such as alumina can modify friction behaviour by smoothing contact surfaces or stabilizing friction layers depending on their proportion (Sugözü et al., 2026). The interaction terms further highlight synergistic and antagonistic effects. The strong positive interaction between Bauhinia and alumina (12.7294) suggests that a balanced combination enhances friction, likely due to improved load-bearing capacity and tribo-film formation. However, the negative interactions between Bauhinia– $\text{CaCO}_3$  (−14.93576) and alumina– $\text{CaCO}_3$  (−2.4907) indicate that excessive filler combinations may reduce COF due to particle agglomeration or excessive smoothing of the contact interface. This aligns with recent studies showing that brake pad composition strongly governs friction stability and stick–slip behaviour through changes in contact mechanics and surface films (Liu et al., 2026).

#### 3.2.2 Effect and interaction of process parameters on COF of BTP brake pad

The process model in Equation (9) shows that CP (0.0097) and Ct (0.0079) positively influence COF, indicating that increased densification and prolonged curing enhance interfacial bonding and structural integrity, leading to improved frictional performance.

$$\text{COF} = 0.4901 + 0.0097 \text{ CP} - 0.0258 \text{ HT} - 0.0183 \text{ CT} + 0.0079 \text{ Ct} - 0.0017 \text{ CP} * \text{HT} - 0.0250 \text{ CP} * \text{CT} + 0.0230 \text{ CP} * \text{Ct} - 0.0325 \text{ HT} * \text{CT} - 0.0698 \text{ HT} * \text{Ct} - 0.0314 \text{ CT} * \text{Ct} - 0.0385 \text{ CP}^2 - 0.0745 \text{ HT}^2 - 0.0641 \text{ CT}^2 - 0.070 \text{ Ct}^2 \quad (9)$$

This is consistent with studies showing that processing conditions significantly affect tribological properties by altering microstructure and contact characteristics (Ilie and Cristescu, 2024). Conversely, HT (−0.0258) and CT (−0.0183) negatively affect COF, suggesting that excessive thermal exposure may degrade the binder matrix or reduce surface roughness, leading to lower friction. The interaction terms revealed negative interactions such as CP–CT (−0.0250) and HT–CT (−0.0325) indicate that combining high pressure or prolonged holding with high temperature can reduce COF due to over-curing or thermal softening. While positive interaction CP–Ct (0.0230) suggests improved bonding and friction when pressure is combined with adequate curing duration. The negative quadratic terms (CP<sup>2</sup>, HT<sup>2</sup>, CT<sup>2</sup>, Ct<sup>2</sup>) confirm the presence of optimal processing conditions, beyond which COF decreases, indicating non-linear behavior typical of tribological systems.

### 3.3 ANOVA and Statistical Analysis of Optimised Brake Pads

The ANOVA results in Table 5 shows varying model adequacy for both optimal formulation and process parameter designs of the BTP brake pad. The ANOVA results indicate that both formulation and process parameters significantly affect BTP brake pad performance, as all p-values are below 0.05, confirming statistical significance. The relatively high F-values, particularly for COF, suggest strong factor influence on responses. This aligns with recent findings that higher F-values reflect stronger parameter effects on tribological properties such as friction and wear (Gore *et al.*, 2025). The models also exhibit strong goodness-of-fit, with R<sup>2</sup> values ranging from 0.8124 to 0.9900, indicating that most of the variability in responses is well explained by the selected factors, consistent with reported reliability levels of 88–97% in similar ANOVA-based tribological studies (Kolawole & Kolawole, 2024). Importantly, the very low C.V% values (1.04–4.6%) across both formulation and process parameters demonstrate excellent experimental precision and reproducibility, suggesting minimal dispersion and high confidence in the data. Adequate Precision values above 4 further confirm an adequate signal for model discrimination. Overall, the results validate the robustness of the statistical models and highlight the effectiveness of ANOVA in optimizing brake pad formulation and processing conditions (Muthu & Lenin, 2025).

**Table 5:** ANOVA values for the optimisation

| Responses          | F-value | P-value | R <sup>2</sup> | C.V % | Adeq Precision |
|--------------------|---------|---------|----------------|-------|----------------|
| <b>Formulation</b> |         |         |                |       |                |
| <b>Density</b>     | 5.27    | 0.0125  | 0.8124         | 1.04  | 5.47           |
| <b>Hardness</b>    | 7.73    | 0.0242  | 0.9796         | 2.12  | 15.20          |
| <b>COF</b>         | 14.08   | 0.0064  | 0.9393         | 1.59  | 12.19          |
| <b>Process</b>     |         |         |                |       |                |
| <b>Density</b>     | 5.79    | 0.0063  | 0.9900         | 4.6   | 15.44          |
| <b>Hardness</b>    | 8.30    | 0.0419  | 0.8440         | 2.94  | 13.65          |
| <b>COF</b>         | 14.10   | 0.0078  | 0.9722         | 2.25  | 12.55          |

### 3.4 Effect of Optimised Formulation and Process Parameters BTP Brake Pad Properties

#### 3.4.1 Effect of optimised formulation of BTP brake pad

Figures 3 (a), (b), (c), and (d) showed the optimal desirability, hardness, density, and COF plots for a locally developed compressed BTP brake pad incorporating alumina and  $\text{CaCO}_3$  as fillers. It has been reported that the desirability function, ranging from 0 to 1, indicates the optimal balance of mechanical, physical, and tribological properties. A desirability score of 0.835 in Figure 4(a) confirms the best material composition for enhanced performance. It could be observed from the optimisation results that the grain size of  $20 > X > 40$  was predicted to be the optimal grain size, indicating fine grain size contributed to the improved COF, Hardness, and density of the BTP brake pad. The finest grain size (100–120 mesh) produced higher COF, as reported by Karaca & Can (2021). This is likely due to the increased contact surface area from the tighter packing density. The coarsest grain size (20–40 mesh) also gave high COF through ploughing resistance from rougher surfaces. In contrast, the intermediate grain size (40–72 mesh) yielded the lowest COF, likely because it balanced packing density and binder distribution.

The hardness values increased with higher alumina and  $\text{CaCO}_3$  content and decreased with high grain size, which is consistent with the abrasive role in friction composites, as reported by Chauhan *et al.* (2021) and Adekunle *et al.* (2023), who used seashell as a mineral filler for its high calcium carbonate content. Predicted optimal formulation was obtained as 323.65 HV as shown in Figure 4(b), and the hardness also increased with a decrease in Bauhinia content since softer fibres were replaced by harder constituents, in line with Popoola *et al.* (2021).

The predicted optimal formulation revealed  $1.79 \text{ g/cm}^3$  density, shown in Figure 3 (c). The sample density decreased with increasing Bauhinia content, reflecting the lower density of organic fibres compared to inorganic fillers, consistent with the findings of Popoola *et al.* (2021). In contrast, density increased with higher calcium carbonate content and alumina content, owing to their higher specific gravity, as observed by Adekunle *et al.* (2023) and Chauhan *et al.* (2021). While the COF ( $\mu$ ) was experimentally characterized in this study, the composition and properties of the optimized BTP brake pad allow for a reasoned estimation of its likely frictional behaviour. The formulation contains key ingredients known to influence COF, which provide an organic, char-forming base (Sathyamoorthy *et al.*, 2022; Nwankwo *et al.*, 2025). It could be observed that the optimal formulation revealed 0.301 as the predicted COF, achieved with  $20 > X > 40$  grain size. Based on the balance of these constituents and comparisons with similar agro-waste composites reported in the literature (Nwankwo *et al.*, 2025; Achebe *et al.*, 2019; Onyenanu *et al.*, 2024), the expected dry coefficient of friction for this composite likely falls within a range of  $\mu \approx 0.30 - 0.45$ . This range is typical for non-asbestos organic (NAO) brake pads designed for low-to-medium duty applications, offering a stable and predictable friction level without the aggressive bite of performance-oriented.

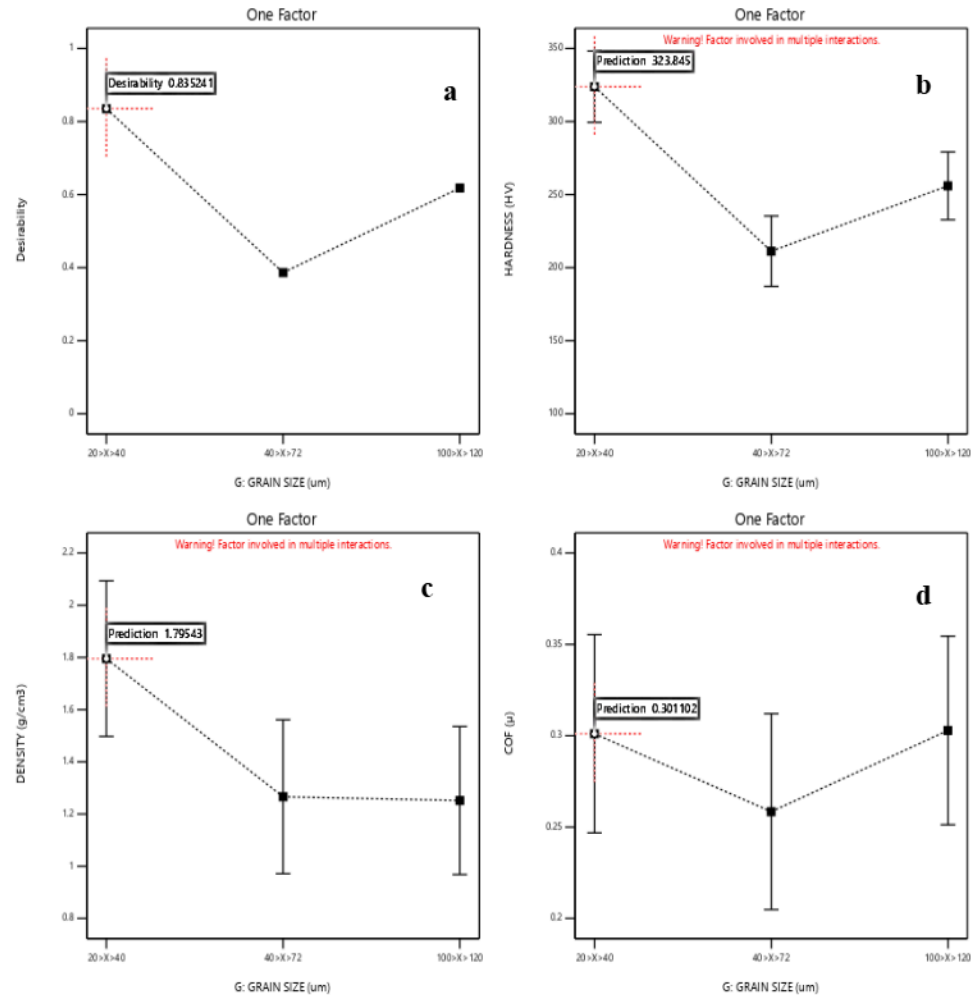
Component Coding: Actual  
 Factor Coding: Actual

#### All Responses

X1 = G

#### Actual Components

A = 15.4563  
 B = 14.5437  
 C = 24  
 D = 10  
 E = 6  
 F = 30

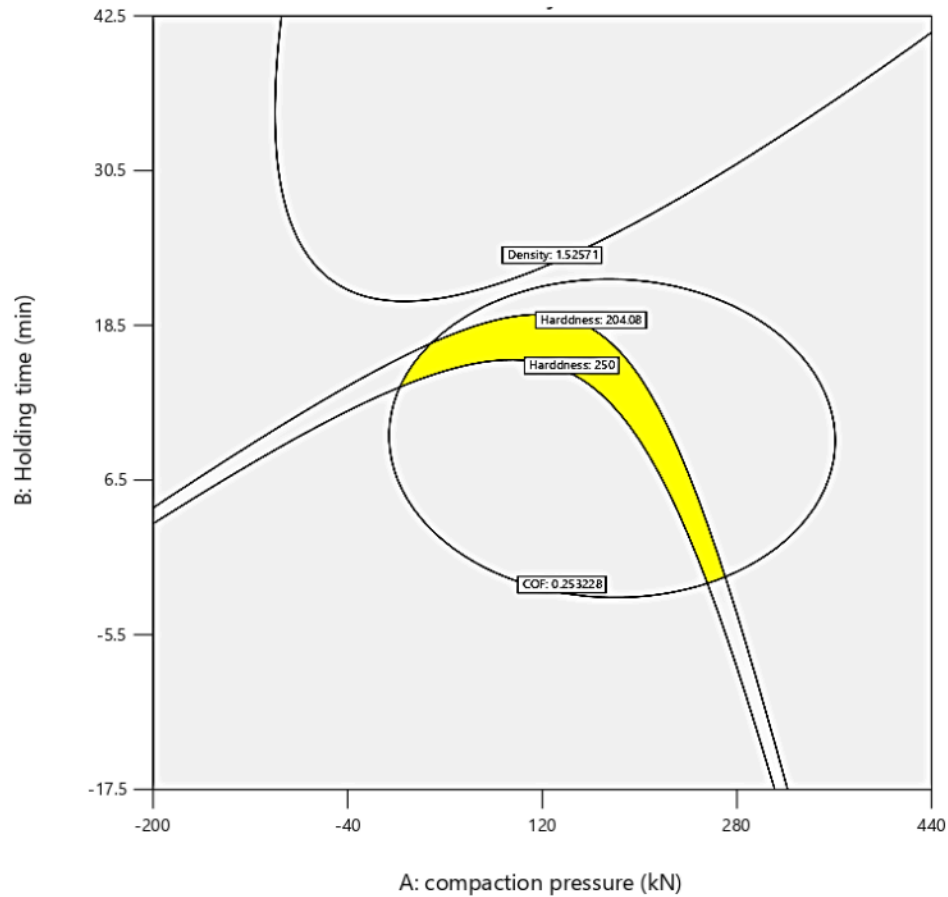


**Figure 3:** Optimal Formulation Results (a) Desirability, (b) Hardness, (c) Density, (d) COF

#### 3.4.2 Optimised process parameters of BTP brake pad

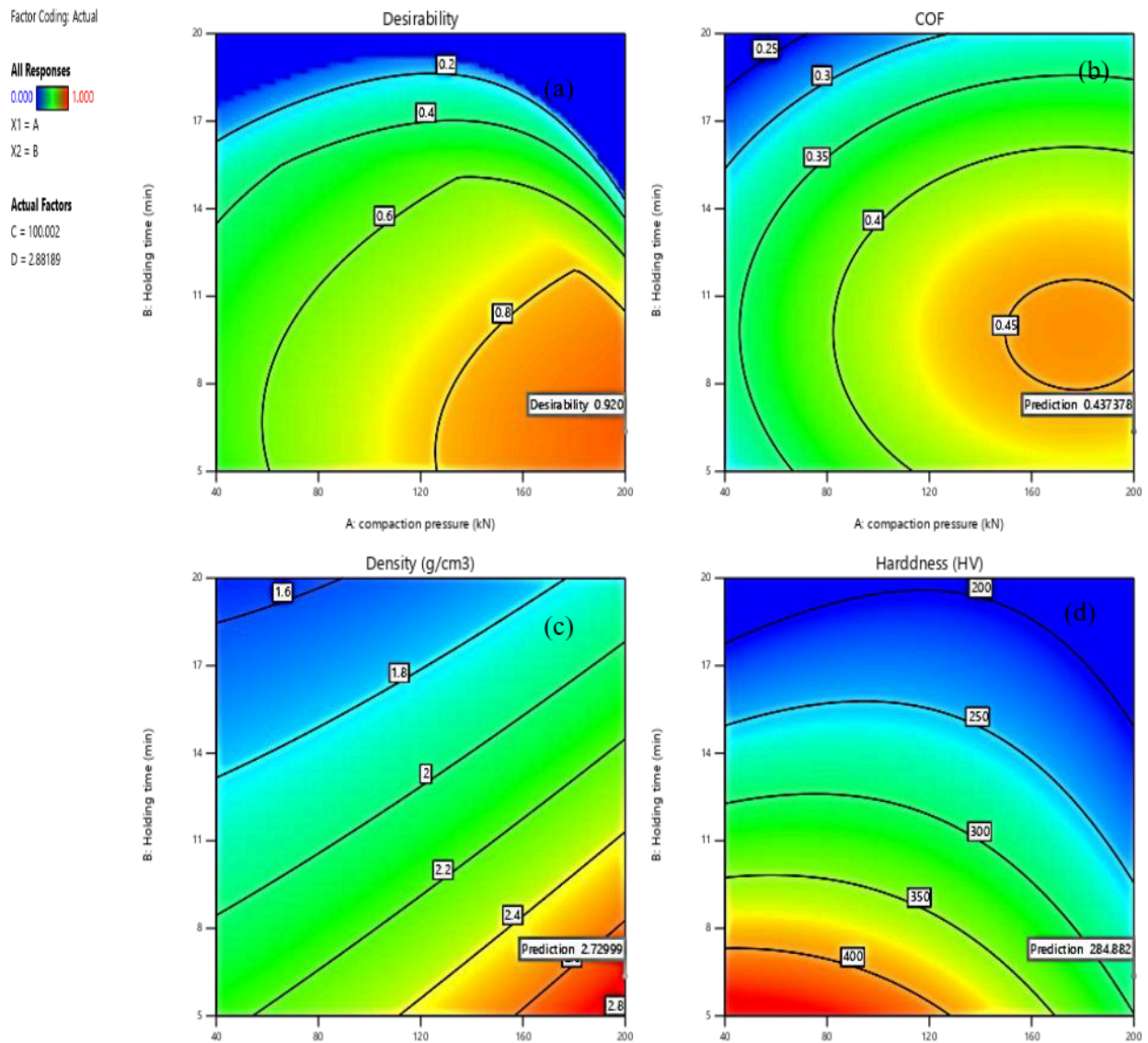
The process optimisation further refined the performance of the optimal formulation by adjusting compaction and curing conditions. From the overlay plot shown in Figure 4, optimal process parameters were obtained at the 0.437 COF, 2.72 g/cm<sup>3</sup> density, and 285.03 Hv with a compaction force of 200 kN, holding time of 2 min, curing temperature of 100 °C, curing time of 2.8 hrs.

Figures 5 (a), (b), (c), and (d) showed the optimal contours of desirability, hardness, density, and COF plots for a BTP brake pad using optimisation of process parameters with predicted curing temperature of 100°C and curing time of 2.88 hours. Nevertheless, several two-factor interactions (compaction time, compaction pressure, curing temperature, and curing time) were significant, suggesting that hardness, density, and COF are influenced by the combined effects of compaction and curing conditions rather than by single parameters. However, the contour graphs showed the interactions of compaction time against the compaction pressure. A desirability score of 0.920 in Figure 9a indicates the best process parameters to enhance performance. It has been reported that the desirability function, ranging from 0 to 1, indicates the optimal balance of mechanical, physical, and tribological properties.



**Figure 4:** Overlay Plot for Optimisation of Process Parameters

A positive interaction between compaction time and pressure indicates that extended compaction combined with longer curing reduces COF, consistent with densification and enhanced crosslinking, producing a stiffer surface in agreement with Huang *et al.* (2022). Yusubov (2021) further highlighted that COF generally increases with physical properties such as hardness and density, supporting the observed influence of these parameters on frictional behaviour. The quadratic effect of compaction pressure revealed a non-linear trend; COF initially increased at lower pressures as densification reduced porosity and increased contact surface, then decreased beyond an optimum as resin overflow produced smoother and harder surfaces. The predicted COF for compaction time against pressure revealed 0.437 showed in Figure 9b, indicating that optimal formulation parameters significantly affect COF, and process conditions were the dominant factor, as supported by Gunjal and Chougule (2022). Density also increased with compaction force, which reduced porosity and improved particle packing, in agreement with (Lawal *et al.*, 2017). While compaction pressure alone was highly significant, other process variables showed weaker individual effects. However, the density of 2.72 g/cm<sup>3</sup> shown in Figure 5 (c) was predicted at higher compaction pressure with low compaction time. This suggests that optimal densification depends on the synergy between compaction and curing conditions rather than on single parameters. The hardness contour graph shown in Figure 5 (d) revealed 284.86 as the predicted hardness for the 2-factor interactions. These combined effects produced hardness values that exceeded those of the commercial pad. Higher compaction pressure and curing temperature enhanced hardness and improved resin crosslinking, as reported by Huang *et al.* (2022) and Adekunle *et al.* (2023).



**Figure 5:** Optimal Process Results for (a) Desirability, (b) COF, (c) Density, and (d) Hardness

### 3.5 Wear Resistance Assessment

Three samples were tested and 10.12 mm/mm<sup>3</sup> were obtained as the wear rate of the optimised process parameters sample. The wear rate decreased with higher hardness and density, consistent with the findings of Abutu *et al.* (2021). Samples with higher alumina and calcium carbonate contents showed improved wear resistance, while increased Bauhinia content reduced wear resistance due to fibre pull-out, in agreement with Onyeneke *et al.* (2014) and Lawal *et al.* (2017). Sequential optimisation produced composites with wear resistance values superior to the commercial pad wear rate (4.17 mm/mm<sup>3</sup>).

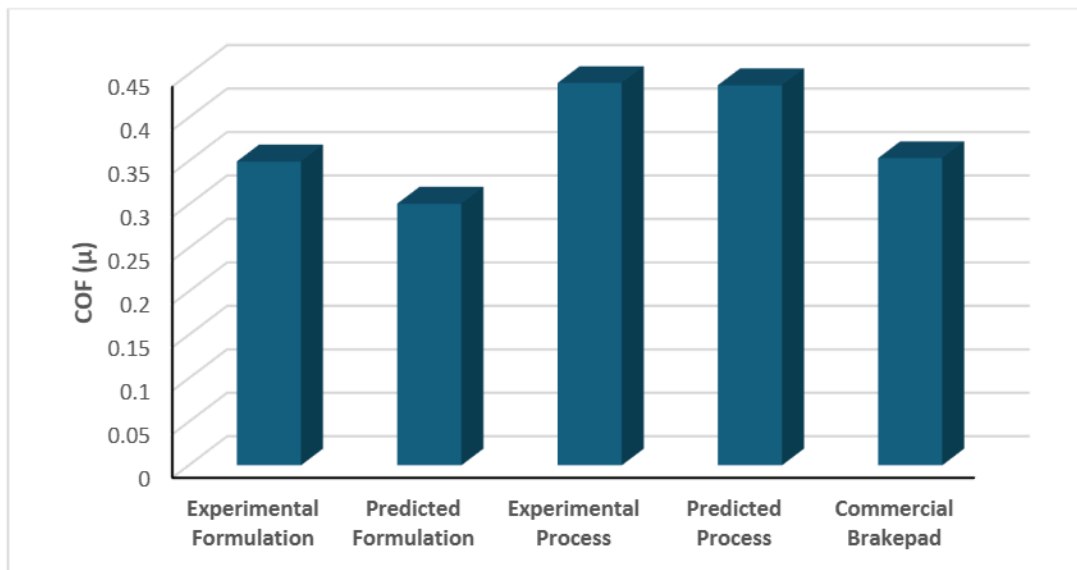
### 3.6 Validation of Optimised and Commercial Brake Pad Parameters

The comparison between experimental, predicted, and commercial brake pad properties shown in Table 6 demonstrates the reliability and performance gains of the optimised *Bauhinia thonningii* formulation. For formulation parameters, the experimental COF (0.3497) closely matches the commercial brake pad (0.35345), indicating comparable frictional performance. At the same time, hardness (257.42 HV) exceeds the commercial value (206.94 HV), suggesting improved frictional behaviour and similar density. The predicted values show higher hardness (323.66 HV) and density (1.79 g/cm<sup>3</sup>), indicating model overestimation but consistent performance trends. Based on the balance of these constituents and comparisons with similar agro-waste composites reported in the literature (Nwankwo *et al.*, 2025; Achebe *et al.*, 2019; Onyenanu *et al.*, 2024), the expected dry coefficient of friction for this composite likely falls within a range of COF  $\approx$  0.30 - 0.45.

**Table 6:** Validation of Optimised and Commercial Brake Pad Parameters

| Sample                                     | COF ( $\mu$ ) | Hardness (HV) | Density (g/cm <sup>3</sup> ) |
|--------------------------------------------|---------------|---------------|------------------------------|
| <b>Experimental Formulation Parameters</b> | 0.3497        | 257.42        | 1.52                         |
| <b>Predicted Formulation Parameters</b>    | 0.3011        | 323.66        | 1.79                         |
| <b>Experimental for Process Parameters</b> | 0.43998       | 254.84        | 1.84                         |
| <b>Predicted Process Parameters</b>        | 0.43738       | 284.88        | 2.72                         |
| <b>Commercial Brake Pad</b>                | 0.35345       | 206.94        | 1.52                         |

For process parameters, the experimental COF (0.43998) and predicted COF (0.43738) show excellent agreement, validating the model accuracy. The COF parameters shown in Figure 6 revealed that experimental and predicted values are highest, indicating that the sequential optimal formulation and process parameters improve the COF. These values demonstrate that sequential optimisation was effective in balancing the influence of formulation and processing, resulting in a brake pad composite that matched or exceeded the performance of the commercial control sample. The increased density (2.72 g/cm<sup>3</sup> predicted) reflects enhanced compaction and bonding, contributing to improved structural integrity. These findings align with studies reporting improved tribo-mechanical properties through optimisation of natural fibre brake pads.



**Figure 6:** Validation Parameters for COF

#### 4.0 Conclusion

This study successfully developed and optimised a *Bauhinia thonningii*-based (BTP) brake pad using a sequential formulation and process-driven Design of Experiments (DoE) approach. The formulation results showed that COF (0.2266–0.3471), hardness (135.60–329.64 HV), and density (0.90–1.85 g/cm<sup>3</sup>) were strongly influenced by material composition. The optimal formulation (Run 2) achieved COF  $\approx$  0.301, hardness of 329.64 HV, and density of 1.85 g/cm<sup>3</sup>, demonstrating improved hardness compared to the commercial control pad (206.94 HV), though with slightly lower COF and density. Process optimisation significantly enhanced performance, with COF ranging from 0.2532–0.4900, hardness from 204.08–434.00 HV, and density from 1.53–2.73 g/cm<sup>3</sup>. The optimal process condition (Run 3) produced  $\mu$  = 0.4900 and density = 1.84 g/cm<sup>3</sup>, outperforming the commercial pad ( $\mu$  = 0.3535, density = 1.52 g/cm<sup>3</sup>). Statistical analysis confirmed density and COF as significant parameters ( $p < 0.05$ ), with strong model reliability for process optimisation. Validation results showed excellent agreement between predicted and experimental COF (0.43738 vs 0.43998), with improved hardness ( $\approx$ 257 HV) and density ( $\approx$ 1.84–2.72 g/cm<sup>3</sup>). Overall, the optimised BTP brake pad demonstrated superior tribo-mechanical performance, confirming its potential as a sustainable alternative to conventional brake materials.

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