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Innovative use of chrome-containing waste and jute fibre in the production of biodegradable therapeutic insoles

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This study investigates the potential of repurposing chrome-containing waste (CCW) and jute fibre (JF) into value-added products by developing a foot pressure composite (FPC). The FPC was fabricated using a leather-based composite (LBC) and evaluated for its functional, thermal, morphological, mechanical, and biodegradation properties. Plantar pressure measurements conducted on healthy individuals wearing FPC insoles revealed an enhanced pressure distribution effect on the foot. The findings indicate that FPC outperforms conventional insoles by offering improved pressure modulation and meeting the mechanical requirements essential for insole applications. Furthermore, the composite demonstrated notable biodegradability. This research highlights a sustainable and economically viable approach for converting CCW and JF into therapeutic footwear solutions, contributing to income generation, environmental protection, and waste recycling technology.

Keywords: Chrome waste, Foot therapy, Green products, Jute fibre, Product innovation, Sustainable manufacturing

1 Introduction

Leather waste generated during tannery treatment and production operations, such as chrome-containing waste (including chrome shavings, trimmings, splitting, and completed leather wastes), is a significant environmental concern due to its volume and toxicity. Currently, only a small percentage of this waste is recycled into low-value products, including solid biofuels, hydrochar, biomethane, bioenergy, construction materials, insulating materials, and blended bricks[1]. Chrome-containing waste, in particular, is frequently discarded and ends up in landfills, contributing to environmental degradation. Recent research has explored innovative methods for repurposing this waste into valuable products. For instance, Senthil *et al*[2] developed regenerated flexible sheets (RFS) using chrome-containing waste, which has been successfully utilised in the production of various leather products.

Natural fibres are classified into groups, including fruit, bast, seeds, and leaves, based on their origin. The majority of these are regarded as leaf fibres and bast due to their advantageous renewability, biodegradability, affordability, and mechanical properties. Jute fibres are highly valued due to their robustness, superior insulating qualities, and 20% moisture content. They are also widely known for being delicate. Compared to fibre glass fibres, which are used to reinforce thermoplastics, natural fibres are 35–40% lighter and pose fewer health and equipment-related hazards during processing[3].

The development of recycled leather boards using water-based natural binders offers a promising route for the sustainable utilisation of tannery waste. Natural binders serve as environmentally friendly adhesives integrating leather waste such as chrome shavings, trimmings, and split leather into cohesive, durable boards[4]. This innovative approach not only enhances the mechanical properties of the recycled leather boards, making them suitable for various applications, but also aligns with sustainable practices by reducing reliance on synthetic chemicals and minimising environmental impact. Recent advancements have demonstrated that natural binder-based processes can effectively transform low-value leather waste into high-value products, paving the way for more sustainable waste management strategies in the leather industry[5].

Building on this foundation, the fabrication of foot pressure composites (FPC) from leather board composites (LBC) represents an innovative strategy that combines waste management with health-enhancing functionality. FPCs utilise leather waste to

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create durable insoles featuring nodular patterns that stimulate reflex zones of the foot, thereby improving blood flow, vitality, and organ function[6]. Thus, using LBC in FPC production not only promotes environmental sustainability but also delivers products with inherent reflexology benefits.

Against this background, the present study aims to develop an FPC from chrome-containing leather waste and jute fibre, offering a sustainable approach to utilising chrome leather waste while delivering added health benefits through reflexological stimulation.

2 Materials and Methods

The chrome-containing waste(CCW)was collected from the Central Leather Research Institute, Council of Scientific and Industrial Research, in Chennai, India. As tanned leather is naturally acidic, the material was neutralised using a 2% ammonia solution and 2% sodium bicarbonate (an alkaline salt). Following neutralisation, the shavings were sun-dried for 48 h and processed through a strap-cutting machine to reduce their fibre length.

Isoprene (C_5H_8), a widely used polar rubber, was sourced as natural rubber latex for reference purposes. Jute fibres (JF) were degummed using standard procedures and dried for 24 h at 60 °C in a vacuum oven. A blended agent (1:8 bath ratio) was then sprayed onto the fibres, followed by a 24 h resting period at 23°C in sealed plastic bags. The fibres were subsequently conditioned at 20 ± 2 °C and 65 ± 3% relative humidity. The blended agent consisted of 5% emulsifier, 6% smoothing agent, 3% Vaseline, and 4% penetrating agent in water.

2.1 Development of FPC

FPCs were prepared using CCW, JF, and a natural binder (NB). The CCW was cleaned, neutralised, dried, and shredded as described earlier. The NB solution was prepared using natural ingredients, with optional additives such as plasticisers or cross-linking agents to improve performance. For each batch, 200 g of CCW was mixed with JF in three proportions: 50 g, 100 g, and 150 g. To this mixture, 200 mL of NB was added, and the materials were blended using an industrial mixer until a homogeneous mixture was obtained. The mixture was then transferred to circular projection moulds (projections: 0.5 cm diameter, 0.3 cm height; sheet size: 3 × 3 ft). Pressure was applied to form the composite sheets. The moulded sheets were cured in sunlight for 6 h to ensure adequate bonding and hardening of the binder. After curing, the composites were removed, cooled, trimmed to uniform dimensions, and subjected to quality evaluation. This detailed explanation describes the step-by-step procedure for generating high-quality FPC using the vacuum pressure method (Fig. 1).

2.2 Physicochemical Characterisation (pH, Moisture, Ash, Fat, Cr_2O_3, Hide Substance)

Samples were dried to a constant weight at 105°C and then milled into a fine powder prior to analysis. pH was measured on a 10% (w/v) slurry prepared in

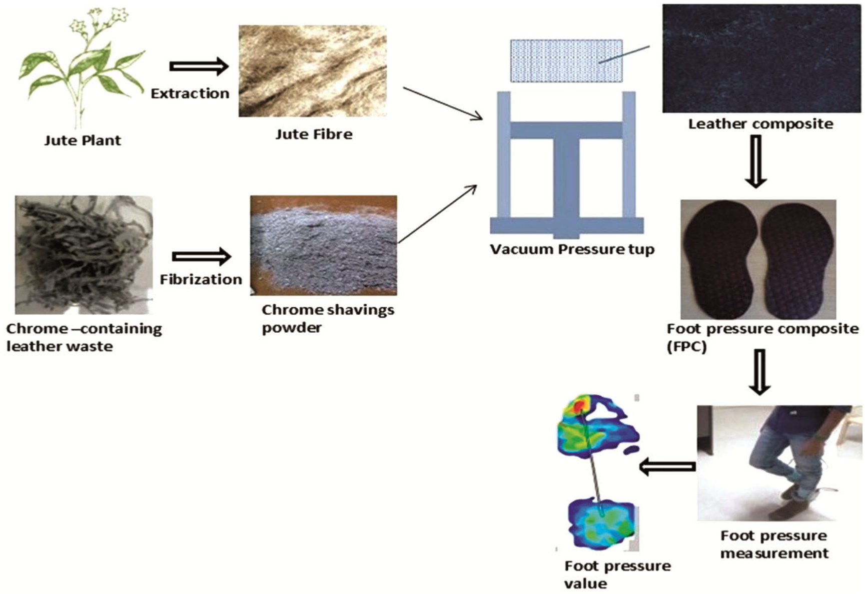


Fig. 1 — Schematic diagram showing the preparation process of FPC

deionised water using a calibrated pH meter (three readings per sample). Moisture content was determined gravimetrically by drying ~2.0 g sample at 105°C to constant weight; moisture (%) = (weight loss/original dry weight) ×100. Ash content was measured by combusting ~2.0 g sample in a muffle furnace at 550 ± 25 °C for 4 h and reporting residue as % ash (dry basis). Total fat was extracted by Soxhlet (petroleum ether, 6–8 h) from ~2.0 g sample; extract was evaporated to dryness and expressed as % fat (dry basis). Chromium oxide (Cr_2O_3) was quantified after acid digestion (HNO_3/HCl or aqua regia) and measurement of total Cr by ICP-OES (or AAS); Cr_2O_3 was calculated from total Cr and reported as % (dry basis). "Hide substance" (collagen/protein content) was estimated by Kjeldahl nitrogen analysis (N × 6.25) on ~0.5–1.0 g sample, or alternately by hydroxyproline assay for direct collagen estimation, and expressed as % (dry basis). All assays were performed in triplicate, and results are reported as mean ± SD. Standard reference materials and method blanks were run to ensure accuracy and recovery.

2.3 Estimation of Chromium (III) and Chromium (VI)

Leaching behaviour was evaluated using the TCLP method (EPA 1311). Air-dried and homogenised samples (<9.5 mm) were weighed (10 g) and extracted with TCLP Fluid No. 2 (acetic acid, pH 2.88; 20:1 liquid–solid ratio) in sealed vessels rotated for 18 ± 2 h. Leachates were filtered (0.45 µm), acidified with HNO_3, and stored at 4 °C. Total chromium was analysed by ICP-OES/ICP-MS, and Cr(VI) was measured using the diphenylcarbazide method at 540 nm. All tests were performed in triplicate with appropriate blanks and controls[7].

2.4 Biodegradation Test (ASTM D5988-03)

The biodegradation of the FPC samples was assessed in accordance with ASTM D5988-03. Specimens were mixed with natural soil and incubated under controlled conditions of moisture and oxygen for 90 days. CO_2 evolution was monitored periodically using sealed respirometric chambers, and the percentage conversion of carbon to CO_2 was calculated to estimate the extent of biodegradation. All tests included soil blanks and were performed in triplicate[8].

2.5 Assessment of the Sensorised Insole System on Human Subjects

Six healthy individuals (three males and three females; age range: 25–35 years) with no lower-limb injuries or known walking dysfunctions were selected for the walking tests. Participants wore regular socks and trainers, and the standard insole was replaced with the FPC insole.To ensure comfort, each participant walked for a minimum of 5 min before testing. They then walked along a 28 m level corridor at their own pace. Walking cadence was measured by counting the number of steps taken in 30 s and to determine their self-selected walking tempo. Each participant completed walking trials using both a normal insole and the FPC insole.

2.6 Statistical Analysis

Physical property measurements of the control sample and FPC variants were performed, and mean values were compared across composites containing different proportions of jute fibre and natural binder. Descriptive statistics, including mean and standard deviation, were calculated based on four independent experiments (n = 4). Statistical analyses were conducted using SPSS (version 20).

3 Results and Discussion

3.1 FPC Characterisation

The FPC are characterised for pH, moisture, ash, fat, chromium oxide content and hide substance on a dry-weight basis. The FPC exhibits a near-neutral pH of 6.5 ± 0.9, with moderate moisture content of 37.43 ± 9.29%, reflecting moderate retained water within the matrix. The ash content is 12.31 ± 13.41%, and the levels of fat (1.57 ± 2.01%) and chromium oxide (1.98 ± 2.38%) are relatively low, confirming its suitability for subsequent processing and application.

3.2 Estimation of Chromium (III) and Chromium (VI)

Both untreated chrome shavings and encapsulated chrome shavings release a maximum of 0.3 ppm chromium (Cr) into the leachate, which is well below the EPA limit of 5 ppm specified under test method D007. Trace levels of other metals, copper (Cu; 0.02 ppm), palladium (Pd; 0.23 ppm), and zinc (Zn; 0.26 ppm) are also detected in the leachate of the encapsulated samples.

3.3 CHNS Analysis

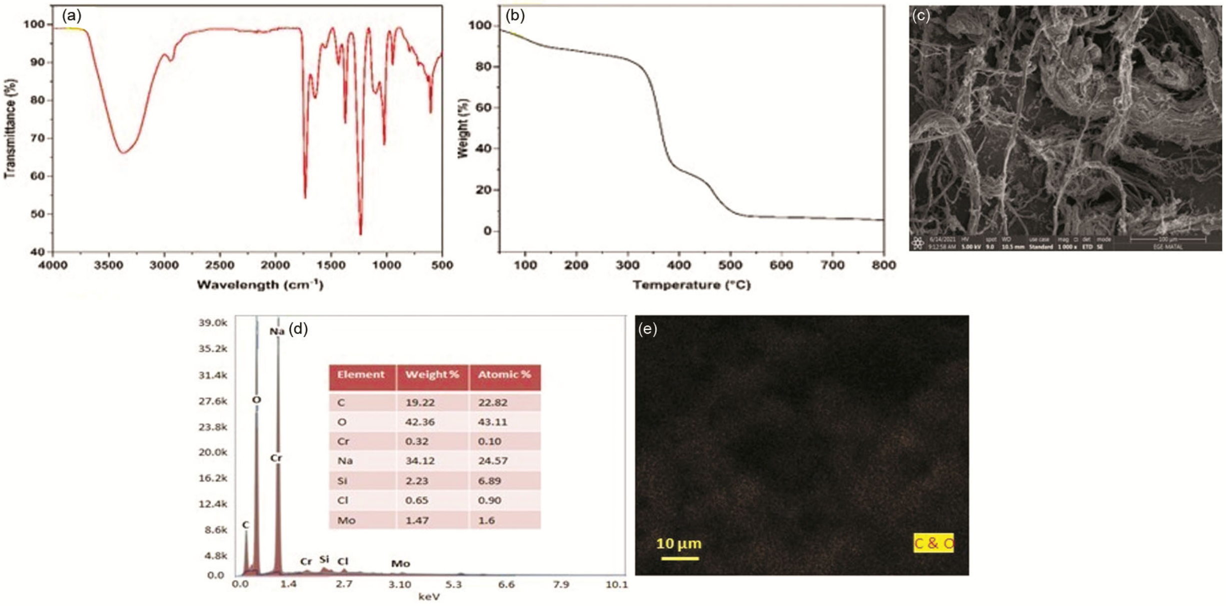
The CHNS analysis of the FPCreveals that carbon is the most abundant element, accounting for 34.75%, followed by oxygen at 29.71%. The composite contains 9.12% hydrogen and 8.321% nitrogen, both of which originate from the amino acid-rich collagen structure of leather waste. The sulphur content is 2.101 %, while the inorganic fraction constitutes 8.345 % of the total composition. The presence of inorganic components and oxygen reflects the contribution of both jute fibre and natural binder.

3.4 FTIR Analysis

The FTIR spectrum of the FPC[Fig. 2(a)] confirms the presence of characteristic functional groups. Broad bands between 3000 and 3500 cm⁻¹ correspond to -OH groups and overlap with -NH stretching. The peak at 2928 cm⁻¹ indicates aliphatic –CH stretching, while the bands at 1650 and 1540 cm⁻¹ correspond to amide I (C=O stretching) and amide II (–NH bending), respectively. Weak bands between 1000 and 1250 cm⁻¹ are assigned to C–O and C–N groups typical of collagen-derived amino acids. Peaks in the 3000–2800 cm⁻¹ region also reflect stretching vibrations of $-CH_3$, $-CH_2$, and -CH groups, indicating that natural rubber possesses an aliphatic hydrocarbon backbone. Additionally, the absence of IR bands at 875 and 712 cm⁻¹ confirms the inhibition of the Cr (III) to Cr (VI) conversion in the chrome shavings encapsulated with polymer-modified emulsion. Chrome shavings account for nearly 70–75% of chromium-containing solid waste generated during leather processing, resulting in approximately 0.8–1.0 million tonnes of waste globally each year. Although small quantities are repurposed for composite leatherboard manufacturing, the majority is still discarded through landfilling or incineration, creating significant environmental and regulatory concerns[9].

3.5 TGA Analysis

Thermogravimetric analysis (TGA) is employed to measure the weight change of an FPC when heated from room temperature to a specified temperature. The TGA curve [Fig. 2(b)] shows three main degradation stages. The first stage involves the loss of moisture and the volatilisation of low-molecular-weight species. The second stage represents primary decomposition, during which rapid weight loss occurs. The third stage corresponds to carbonisation. Rapid weight loss and a rise in temperature are additional signs of the second stage of degeneration. The loss of water molecules is evident during the breakdown process at temperatures exceeding 100 °C. These results align with earlier findings. Sharma *et al.*[10] reported three major phases of thermal degradation in collagen hydrolysate. The first phase (46.05–220.24 °C) showed a 9.67% weight loss due to moisture evaporation. The second major degradation event (220.2–350.98 °C) resulted in a 38.84% weight loss, attributed to the breakdown of protein chains. The thermal degradation results reported here correspond to our present study. The initial degradation temperature observed (220.2 °C) is slightly higher than the value reported by Joseph *et al.*[11] (200 °C), indicating improved thermal stability in our sample. In our analysis, the third phase of



Element	Weight %	Atomic %
C	19.22	22.82
O	42.36	43.11
Cr	0.32	0.10
Na	34.12	24.57
Si	2.23	6.89
Cl	0.65	0.90
Mo	1.47	1.6

Fig. 2 — Characterisation of FPC (a) FTIR spectrum, (b) TGA curve, (c) HRSEM micrograph, (d) EDX spectrum, and (e) elemental mapping

Table 1 — Mechanical properties of FPC

CCW, wt%	JF, wt %	NB solution, mL	Tensile strength, MPa	Elongation at break, %	Flexibility, %	Water absorption, %	Water desorption, %
200	50	200	41.32±2.15	42.68±1.08*	2.71±0.11	21.52±0.22*	24.17±1.55
200	100	200	43.23±1.95*	44.12±0.15	3.71±0.17	22.31±0.11	25.32±1.76*
200	150	200	46.75±2.81	47.54±0.18*	4.87±0.55*	23.45±0.17	26.72±1.13

The data are presented as mean±SD of three individual experiments. * $p < 0.05$, using Duncan's multiple range analysis.

weight loss occurred between 350.98 and 431.35 °C, followed by a final degradation stage from 431.4 to 587.06 °C, resulting in a 12.89% weight reduction, compared with 7.24% reported previously. The residual mass at 587.06 °C was 30.45%. The maximum decomposition rate occurred at 311.75 °C with a rate of 0.766%/°C.

3.6 HRSEM and EDX Analysis

The surface morphology of the coloured FPC is examined using a high-resolution scanning electron microscope (HRSEM). Fig 2(c) reveals a fibrous, well-interlinked architecture with smooth surfaces, suggesting strong adhesion between the jute fibres, natural polymer and chrome-tanned leather waste. The stretched surface features indicate high deformation capacity, consistent with the elastic behaviour of the EVA-based polymer matrix. These observations support the mechanical and tactile performance data. Similar observations have been documented in earlier studies[12]. Energy-dispersive X-ray spectroscopy (EDX) analysis confirms the presence of carbon and oxygen as the major elements [Fig. 2(d)], while elemental mapping [Fig. 2(e)] shows a uniform spatial distribution of elements across the composite surface.

3.7 Mechanical Properties

The mechanical performance of the FPCs is evaluated in terms of tensile strength, elongation at break, flexibility, and water absorption and desorption behaviour (Table 1). These properties are essential for determining the suitability of the composites for applications such as insoles and other value-added leather products. The results show that incorporating natural rubber (NR) and increasing the proportion of jute fibre (JF) contribute significantly to the mechanical improvement of FPC. Tensile strength increases progressively from 41.32 MPa at 50 g JF to 46.75 MPa at 150 g JF. A similar trend is seen in elongation at break, which rises from 42.68 % to 47.54 %, indicating that higher JF content enhances the composite's elasticity. This improvement can be attributed to the intrinsic elastic nature of jute fibres, which reduces brittleness and provides reinforcement to the leather–binder matrix[13].

Flexibility also improves with increasing JF, reflecting the synergistic interaction between the non-polar NR, the natural binder, and the fibrous structure of jute. Previous studies report similar enhancements in rubber-matrix composites reinforced with jute fibre, where flexural and compression strengths are significantly improved with higher fibre concentrations[14]. The present results align with these findings and confirm strong interfacial compatibility between NR, JF, and chrome-containing waste.

Water absorption and desorption are critical parameters because they influence comfort, dimensional stability, and durability in footwear applications. The water absorption values increase slightly with higher JF loading, which is expected due to the hydrophilic cellulose content of jute fibres[15]. Composites with strong water absorption and degreasing capabilities are ideal for preparing footwear and leather products, as they retain a dry surface and minimise slipperiness and microbiological growth[16]. The foregoing results show the composite containing 150 g JF exhibits the most favourable combination of tensile strength, elasticity, flexibility, and moisture-handling performance. These attributes suggest that higher JF content yields a stronger and more resilient composite, making it a promising candidate for use in leather-based functional materials such as foot pressure insoles.

3.8 Biodegradation Study

The biodegradation after 90 days according to ASTM D 5988-03 is shown in Fig. 3. FPC (150g of JF) degraded faster than FPC (50g of JF). Biodegradation study reveals that samples show similar degradation behaviour during the first 20 days; however, the composite with 150 g jute fibre degrades significantly faster thereafter. Increasing environmental concerns have heightened the need to evaluate biodegradability using reliable indicators such as CO_2 production, which is widely employed for assessing soil degradation and composting of polymeric materials[17,18].

3.9 Foot Plantar Pressure Measurement

Foot plantar pressure evaluation provides meaningful insight into how different insole materials influence load distribution across the foot during walking. This assessment is essential because excessive or uneven pressure can affect comfort, gait efficiency, and the stimulation of reflex zones that contribute to the benefits of acupressure.

Fig. 4 depicts the mean peak pressure (MPP) of four key plantar regions while participants wear normal insoles and the developed FPC insoles. Among these regions, the forefoot—which corresponds to the FPC nodular zone—consistently exhibits the highest-pressure values, reaching up to 215 kPa (Fig. 5). This trend indicates that the forefoot bears a substantial portion of body weight during dynamic movement and that the nodulated FPC surface encourages targeted pressure concentration at desired reflex points.

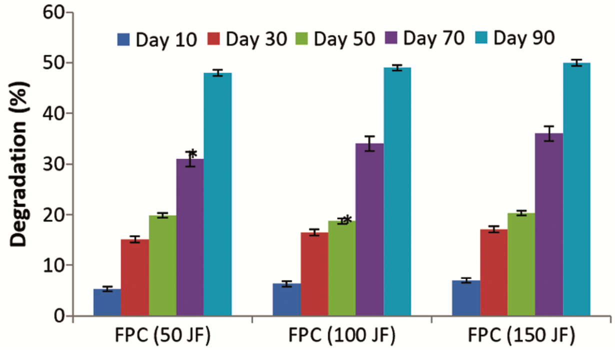


Fig. 3 — Biodegradation behaviour of FPC

A comparison with normal footwear further highlights the influence of sole design on plantar pressure. Trainers with cushioned midsoles reduce peak pressure by up to 20% due to superior shock-absorbing properties. In contrast, the thin and relatively rigid outsoles of both normal and FPC insoles provide less cushioning, resulting in higher pressure intensities. However, in the context of reflexology-based design, such localised pressure is desirable, as it enhances stimulation of specific foot zones.

To obtain a more comprehensive understanding of plantar load behaviour, both pressure and shear forces are analysed. Shear force evaluation is particularly valuable, as high shear levels in conjunction with pressure reveal how the foot interacts with the insole surface during gait. These combined parameters help

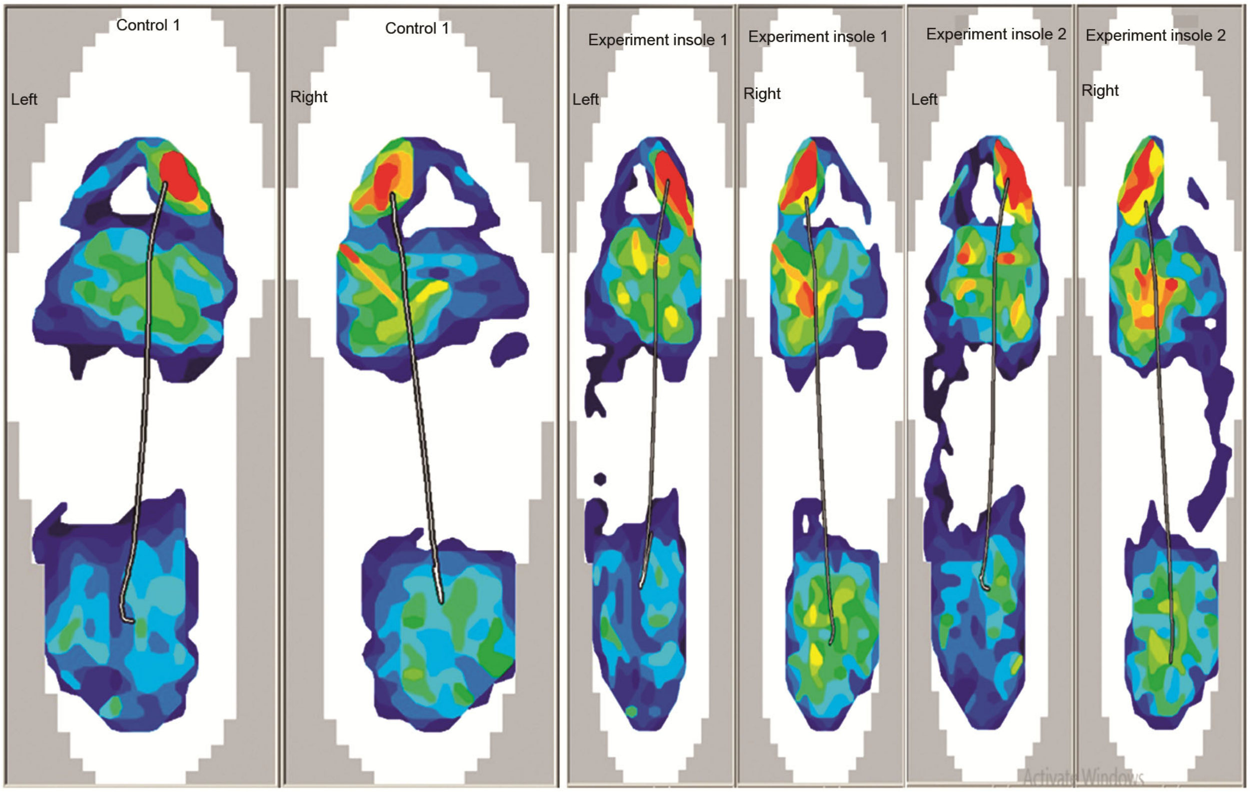


Fig. 4 — Comparative plantar pressure analysis using control and FPC insoles

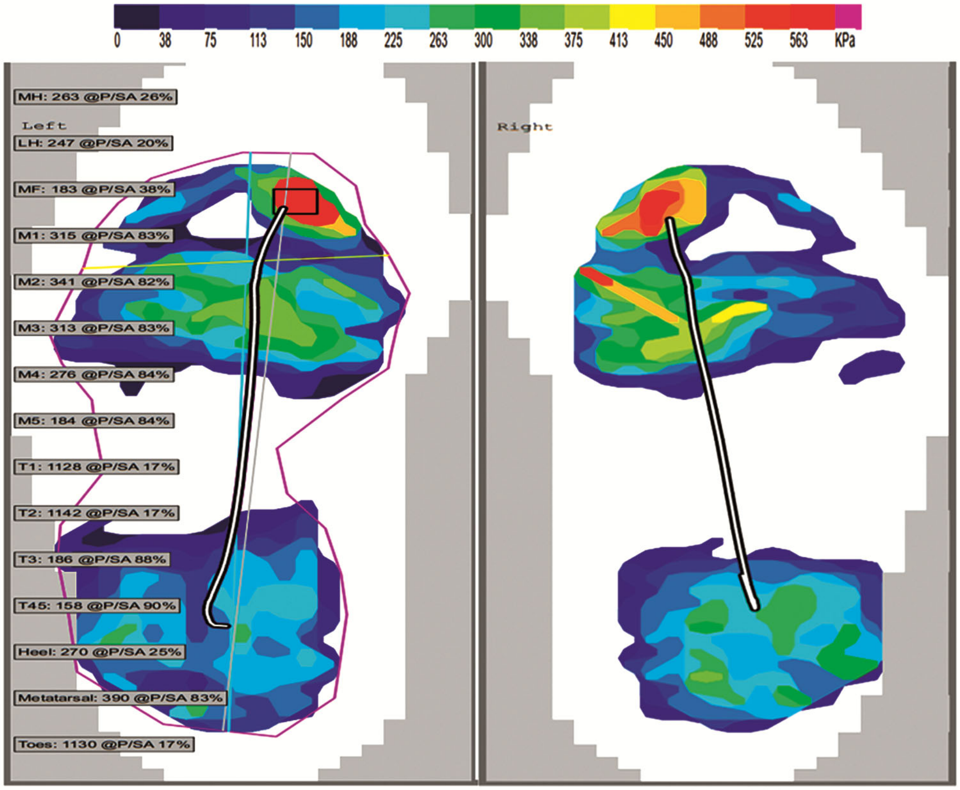


Fig. 5—Peak plantar pressure values recorded for the FPC insole

determine whether the insole design effectively targets reflex points without causing discomfort[19].

The regions of interest are identified according to the sensor positions shown in Fig. 1(a), with an additional limit of 10% in each direction to accommodate any alignment variations between steps. Increased foot pressure can activate reflex points, resulting in improved energy circulation throughout the body. The increased localised pressure generated by the nodules on the FPC insole activates reflex points more effectively, thereby promoting enhanced blood flow, improved energy circulation, and potential wellness benefits associated with reflexology. Importantly, the FPC manufactured from chrome-containing leather waste demonstrates adequate durability and functional performance, confirming its suitability as an acupressure-enabled footbed material[20,21].

Recent studies by Raja and Devarajan[22,23] have shown that integrating natural fibres or nanofillers into composite systems can significantly improve material stability, mechanical properties, and functional performance. Their findings support the current work, where collagen-based or polymer-modified composites similarly demonstrate enhanced structural behaviour and application potential. These parallels underscore the increasing importance of sustainable, biodegradable, and nanoparticle-reinforced materials in advancing next-generation biomedical and industrial applications.

4 Conclusion

This study demonstrates that foot pressure composites (FPC) developed from chrome-containing leather waste, jute fibre, and a natural binder present a viable and sustainable alternative to conventional insole materials. The fabrication process produces a structurally stable composite with sufficient durability, comfort, and functional performance for use in footwear. Plantar pressure analysis reveals that the FPC insole generates targeted and localised pressure, particularly in the forefoot region, enabling effective stimulation of reflex points associated with acupressure benefits.

The integration of nodular projections within the FPC enhances peak pressure distribution while maintaining acceptable comfort levels, thereby supporting its potential application in reflexology-based foot care products. Human subject testing confirms that the composite insole influences load distribution in a predictable manner, offering a balance between rigidity and responsiveness. The findings demonstrate that converting chrome-containing leather waste into functional foot pressure composites supports both resource recovery and value addition, aligning with the principles of the circular economy. The developed FPC insole emerges as a cost-effective, environmentally responsible, and performance-enhancing option for footwear and wellness applications. Future research could explore novel applications and further optimization of this innovative material, contributing to sustainable waste management in the leather industry.

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