UNIVERSITI TEKNOLOGI MARA

AN INTEGRATED CRITIC-TOPSIS FRAMEWORK FOR THE OPTIMAL MATERIAL SELECTION OF NATURAL FIBRE REINFORCED COMPOSITE CAP TOE SHOES

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ABSTRACT

The growing demand for lightweight, high performance, and environmentally sustainable personal protective equipment has driven the need for advanced alternatives to conventional metallic cap toe shoes materials. Although, metallic inserts provide excellent impact resistance, they are associated with excessive weight, reduce ergonomic comfort, and significant environmental burden. Furthermore, the application of natural fibre reinforced composite (NFRC) in cap toe shoes remains limited due to the absence of a systematic and reliable material selection framework capable of addressing multiple conflicting criteria, including mechanical strength, density, and sustainability. This study aims to develop a validated and systematic decision making framework for identifying the optimal NFRC materials for cap toe shoes application. An integrated Multi Criteria Decision Making (MCDM) model combining the Criteria Importance Through Intercriteria Correlation (CRITIC) method and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) was employed to enable objective criteria weighting and robust material ranking. The evaluation considers key performance attributes such as impact resistance, density and environmental sustainability. To enhance robustness and practical applicability, the framework is further integrated with the Plan-Do-Check-Act (PDCA) cycle and implemented using a MATLAB computational model. The top ranked composite material was subsequently analysed using explicit dynamic Finite Element Analysis in ANSYS to evaluate stress distribution, deformation behaviour, and energy absorption under standardised impact conditions. The results identified Ijuk as the potential natural fibre (Pi = 0.5082) and Polyethylene as the most suitable polymer matrix (Pi = 0.6013). The FEA results demonstrated low stress concentration and controlled deformation, confirming the structural suitability of the selected composite under impact loading. Sensitivity analysis further verified the stability and reliability of the ranking outcomes. This study delivers a comprehensive and reliable decision support tool for sustainable material selection in cap toe shoes and aligning with the United Nations Sustainable Development Goals (SDG).

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LIST OF ABBREVIATIONS

Abbreviations

AHP	Analytical Hierarchy Process
ANN	Artificial Neural Network
ANP	Analytic Network Process
COPRAS	Complex Proportional Assessment
CRITIC	Criteria Importance Through Intercriteria Correlation
DM	Decision Making
ESG	Environmental, Soial, Governance
EVA	Ethylene Vinyl Acetate
FAHP	Fuzzy Analytical Hierarchy Process
FEA	Finite Element Analysis
FEM	Finite Element Method
GRA	Grey Relational Analysis
LCA	Life Cycle Assessment
MARCOS	Measurement of Alternatives and Ranking according to COmpromise Solution
MCDM	Multi Criteria Decision Making
NFRC	Natural Fibre Reinforced Composite
NIS	Negative Ideal Solution
PA	Polyamide

PBAT	Polybutylene Adipate Terephthalate
PC	Polycarbonate
PCA	Principal Component Analysis
PDCA	Plan-Do-Check-Act
PE	Polyethylene
Pi	Relative Closeness Coefficient
PIS	Positive Ideal Solution
PLA	Polylactic Acid
PMB	Polymer Modified Binder
PMC	Polymer Matrix Composites
PP	Polypropylene
PPE	Personal Protective Equipment
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PSI	Preference Selection Index
PU	Polyurethane
SAW	Simple Additive Weighting
SDG	Sustainable Development Goals
SWARA	Stepwise Weight Assessment Ratio Analysis
TODIM	Tomada de Decisão Interativa Multicritério
TOPSIS	Technique Order Preference by Similarity to Ideal Solution
VAIC	Value Added Intellectual Capital

VIKOR	VlseKriterijumska Optimizacija I Kompromisno Resenje
WASPAS	Weighted Aggregated Sum Product Assessment

CHAPTER 1
INTRODUCTION

1.1 Research Background

Safety footwear typically weight between 0.9 to 4.4kg, with a consideration portion of this mass attributed to the steel toe cap and anti-penetration plate (Alberto et al. 2024). Additional factors such as material composition, sole configuration, and shaft height also contribute to the overall weight variation (Chiou et al. 2012). The increase mass of safety footwear has been shown to influence lower limb muscle activity, ankle joint motion, and plantar pressure distribution, leading to elevated energy expenditure, oxygen consumption, and metabolic demand among workers (Ochsmann et al. 2016; Pereira-Barriga et al. 2024) Collectively, these physiological and biomechanical effects may compromise postural control and stability during occupational task, thereby predisposing workers to muscle fatigue, a known precursor to musculoskeletal disorder, particularly those affecting the lower limbs (Anderson, Williams, and Nester 2021). According to Arceri et al. (2024), several safety shoes attributes, such as weight, improper fit, and inadequate design may contribute to safety shoes discomfort and negatively affect gait patterns, which is can subsequently increase the likelihood of foot problems among workers.

The natural fibre are commonly used to produce lighter and more durable final products (Rahman and Ariffin 2022). Research related to the application of natural fibre has primarily focused on the automotive industry (Peças et al. 2018). Their low density and lightweight characteristics make them suitable replacements for conventional materials (Ahmad, Choi, and Park 2015). Moreover, natural fibre materials are sustainable and renewable resources (Luhar et al. 2020), and their eco-friendly, non-toxic and biodegradable nature further enhances their appeal (Dixit et al. 2017). It is expected that cap toe shoes made from natural fibre could contributes significantly to products lightweight and environmental sustainability. By selecting appropriate material properties these cap toe shoes can effectively withstand impact loads from flying debris.

The thermoplastic polymer matrix has been widely used as a reinforced material to enhance the mechanical properties of the natural fibres composites, owing to its

recyclability, shorter processing time as (curing is not required), lower cost, and reduced need for toxic solvent (Baghaei, Skrifvars, and Berglin 2013). Therefore, in view of these observed variations, designers are required to make well informed and systematic decisions in selecting the most appropriate NFRC for application in cap toe shoes.

The contemporary era has witnessed a significant increase in the availability of environmentally sustainable products across many markets. The integration of environmental considerations into the product design and development process is a fundamental aspect of environmentally conscious design, as outlined in the ISO standard 14062 (ISO, 2002). This integration process comprises several crucial elements, including the reduction in the use of virgin natural resources, the incorporation of environmentally sustainable energy sources, improvements in product recyclability and biodegradability, and the maximisation of product value at the end of its operational lifespan (Mayyas et al. 2012). To effectively commercialise and generate substantial financial returns from an innovation the process requires the creation and advancement of tangible items.

Ensuring that safety footwear meets strict performance requirements while reducing weight and environmental impact remains a significant challenge. Conventional metallic cap toe shoes, although widely adopted for their high-strength and impact resistance, are associated with excessive weight. These limitations have driven increasing interest in alternative lightweight materials for protective footwear applications. When producing environmentally friendly products, it is desirable to select materials that have minimal impact on the Environment. Consequently, 'green' materials such as natural fibre composites are widely used in various product applications. Natural fibre composites serve as excellent alternatives to steel because they are readily available, highly corrosion-resistant, recyclable, and reusable.

In this research, a structured Decision Making (DM) framework based on their integration of the CRITIC-TOPSIS methods was employed to objectively rank and select natural fibre and polymer matrix materials for cap toe shoes applications. The selected composite systems were subsequently evaluated using explicit dynamic FEA to assess their impact behaviour. Throughout the development of the natural fibre composite cap toe shoes, both customer requirements and environmental sustainability considerations were considered.

1.2 Problem Statement

Previous studies have substantiated that the utilisation of natural fibres in such products can significantly enhance their capacity to absorb impact energy, provided they are applied appropriately. The problem statement of this research is to address the existing gap in the use of natural fibres for the purpose of improve the impact strength of cap toe shoes. The purpose is intended to be achieved by a thorough and methodical study, for addressing these problem statements:

Problem Statement 1: The growing demand for lightweight, high performance, and environmentally sustainable materials has driven growing interest in NFRC (Kamarudin et al. 2022). However, their broader use in engineering is still limited due to inconsistent material properties, variation in fibre quality, sensitivity to moisture, and the lack of a systematic and reliable material selection framework (Kaufmann et al. 2025; Shaker and Fauster 2025; Yasir et al. 2021).

Material Selection for NFRC is inherently a MCDM physical characteristics, durability and sustainability must be evaluated simultaneously in a balanced manner (Noryani et al. 2018; Wang, Reza, and Pandu 2024). Although hybrid MCDM approaches such as AHP-VIKOR and other integrations have been widely applied to improve DM quality, their first limitation is that many of these hybrid models combine subjective expert driven weighting with objective data driven weighting, but the final results remain highly dependent on the chosen fusion mechanism, weighting coefficient, or aggregation rule used to balance the two components. As a result, the final ranking may reflect not only the actual performance of alternatives, but also the analyst's choice of integration strategy, thereby reducing transparency and reproducibility (Malefaki et al. 2025; Yennylawati et al. 2026).

More broadly, current hybrid MCDM integrations often flexibility and comprehensiveness, but they still suffer from method sensitivity, computational complexity and limited scalability. Many studies focus primarily on the final ranking results without fully addressing how methodological choices, weighting structures, and parameter settings influence robustness and decision reliability. Therefore, there remains a need for a more robust MCDM integration framework that minimises subjectivity, reduces dependence on subjective fusion rules, and provides more stable and reproducible ranking outcomes (Wei 2025).

i. Despite the increasing importance of natural fibre composite selection, only

a limited number of studies have investigated the hybrid integration of the CRITIC and TOPSIS methods in this area. This decision problem inherently complex because of variability in material behaviour and the presence of multiple conflicting performance criteria. Although MCDM techniques are widely recognised as effective tools for DM under uncertainty, existing studies have mainly employed subjective weighting techniques or standalone methods, which may affect the robustness and reliability of the final decision. Moreover, the applicability of objective CRITIC based weighting combined with TOPSIS ranking for natural fibre composite prioritisation has not yet been systematically examined. Hence, the development of a structured and reliable MCDM framework tailored specifically to natural fibre composite material selection remains an important research gap.

Problem Statement 2: The selection of suitable natural fibre materials for cap toe shoes design remains challenging because the material must satisfy multiple requirements such as strength, durability, low weight, and sustainability while dealing with variability in natural fibre properties. Although natural fibre composites offer significant advantages, their application in cap toe shoes structures is still limited due to the lack of systematic and reliable material selection framework. Conventional selection methods often rely on empirical judgement or limited criteria, which may lead to inconsistent and sub-optimal decisions when multiple conflicting factors must be considered. While MCDM methods have been applied in engineering, their use for selecting natural fibre materials specifically for cap toe shoes design remains limited.

Therefore, an objective structured decision support approach is required. The integration of CRITIC for objective weighting and TOPSIS for ranking provides a systematic framework capable of improving decision accuracy and reducing subjectivity, hence this study aims to develop a CRITIC-TOPSIS based framework to systematically evaluate and select suitable natural fibre materials for cap toe shoes.

ii. At present, research on the selection of suitable natural fibres for cap toe shoes application remains limited. Therefore, a systematic DM tool is needed to identify the most appropriate natural fibre material for use in cap toe shoes.

Problem Statement 3: The selection of an appropriate polymer matrix composites (PMC) for cap toe shoes design is challenging because the material must

simultaneously satisfy strength, impact resistance, durability, weight, and sustainability while ensuring consistent manufacturability and performance. Although MCDM methods have been applied in material, the integration of continuous improvement and computational implementation for PMC evaluation in cap toe shoes applications remains limited, highlighting the need for a structured and reliable decision framework.

iii. To date, MATLAB based implementations for performing calculations using the hybrid CRITIC-TOPSIS MCDM methods remain limited. This creates a practival challenge for researchers seeking an efficient computational tool to apply the method systematically and accurately

Problem Statement 4: The impact performance of NFRC cap toe shoes structures remain insufficiently understood due to the complex and heterogeneous behaviour of natural fibre composites under dynamic loading. Consequently, a reliable computational approach is required to evaluate in early stages to evaluate the structural response of NFRC cap toes shoes under impact conditions.

iv. At present, the development of explicit dynamic finite element models for simulating the impact behaviour of NFRC cap toe shoes structures using ANSYS workbench remains limited.

Based on the above discussion, the present study is motivated by four interconnected research gaps. First, natural fibre reinforced composites remain underutilised in cap toe shoes applications despited their potential as lightweight and sustainable alternatives to conventional metallic and synthetic materials. Second, the selection of suitable natural fibres materials is complicated by the variability of fibre properties and the presence of multiple conflicting performance criteria. Third, limited studies have developed an objective CRITCI-TOPSIS based DM framework specifically for natural fibre and polymer matrix selection in cap toe shoes design. Fourth, existing material selection studies ofthen lack mechanical validation under impact loading conditions. Therefore, this study develops an integrated CRITIC-TOPSIS framework, supported by PDCA, MATLAB computation, sensitivity analysis, and Finite Element impact simulation, to provide a reliable and systematic approach for selecting natural fibre reinforced composite materials for cap toe shoes.

1.3 Research Objectives

The research objectives are as follows:

a) To construct a comprehensive framework for prioritising natural fibre composite materials through the CRITIC-TOPSIS MCDM approach

b) To perform a material selection for natural fibres material in the cap toe shoes design using CRITIC-TOPSIS MCDM approach

c) To develop an investigate PDCA-CRITIC-TOPSIS framework, supported by MATLAB coding, for PMC material selection in cap toe shoes design to improve decision reliability

d) To simulate finite element models of NFRCs cap toe shoes through explicit dynamic impact analysis using ANSYS workbench

1.4 Scope and Limitation of Study

The safety footwear application addressed in this research is industrial use, specifically composite cap toe shoes for workers operating in environments with foot injury risk due to falling or rolling objects, where compliance with protective toe cap performance requirements is essential. The scope of this study has been determined based on the following Research Objective:

i. Construction of Framework
    a) The scope was focused on the construction of a decision support framework based on the CRITIC-TOPSIS method. The framework was intended to support systematic comparison and ranking within the defined study context.

ii. Performing Material Selection for Natural Fibre Material
    a) The study was focused to the evaluation and ranking of selected natural fibre materials for cap toe shoes applications only. The assessment was based on predefined mechanical, physical, and sustainability related criteria relevant to safety footwear performance.
    b) The analysis relied on secondary data obtained from the literature and reported material properties only.

c) The material selection outcomes were intended to support comparative DM within the defined case study and were not generalised to other footwear components or composite applications.

iii. Investigation of Polymer Matrix

a) The study was focused to ranking selected polymer matrix materials identify the most suitable options for cap toe shoes applications only. The evaluation was based on predefined mechanical, physical, and sustainability criteria relevant to safety footwear performance.

b) The numerical implementation was confined to a MATLAB based computational model developed solely to perform CRITIC-TOPSIS calculations.

iv. Simulation of Finite Element Models

a) Conducting an impact analysis on the proposed NFRC cap toe shoes only.

1.5 Significance of Study

This study aims to highlight the environmental requirements and potential impacts associated of cap toe shoes. Since natural fibres are biodegradable, their utilisation directly supports the Unites Nations SDGs, particularly SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action). The development of natural fibre based biocomposites align with SDG 9 by promoting innovative material solutions that reduce dependency on conventional, non-renewable resources. Meanwhile, their biodegradable nature and lower environmental footprint contribute to SDG 13 through climate friendly material selection and reduced long term ecological impact.

Beyond environmental benefits, the integration of natural fibre reinforced polymer composites also presents significant safety potential, especially for applications such as cap toe components in safety footwear. Cap toe shoes require materials that can withstand high impact loads, resist deformation and maintain structural integrity under demanding conditions. Recent finding indicates that certain natural fibres process favourable mechanical properties such as high specific strength, good energy absorption and resistance to cracking, that make them viable for

cushioning, protective and sealing functions. These characteristics suggest that natural fibre could be engineered to meet or exceed the safety standards required for protective cap toe shoes.

From an industrial perspective, the possibility of developing lightweight, sustainable, and structural efficient cap toe shoes components offer a promising pathway for commercialisation. The substitution of synthetic fibres with natural alternatives not only reduces environmental burdens but also supports the global transition towards greener manufacturing practices. In summary, incorporating natural fibres into cap toe shoes provides a dual advantage; enhancing user safety while promoting environmental sustainability, ultimately contributing to industrial innovation.

1.6 Thesis Organisation

The aim of this thesis is to develop an integrated DM framework for selecting NFRC materials for cap toe shoes applications. The framework combines the CRITIC-TOPSIS MCDM techniques with FEA to evaluate mechanical performance and impact behaviour. This thesis documents the framework development, material ranking, and numerical validation, and is structured into five chapters covering these aspects in a systematic manner.

CHAPTER 1 presents an Overview of the study and outlines the underlying motivation driving the research. It further explained the problem statement and describes the implementation framework adopted in this study. In addition, relevant background information and definitions of key terms utilised throughout the study are provided to establish clarity and contextual understanding.

CHAPTER 2 critically reviews the literature on NFRC and MCDM methods for cap toe shoes applications. Emphasis is placed on the mechanical and impact performance of natural fibre materials, as well as the application of CRITIC-TOPSIS and related MCDM frameworks for systematic material selection.

CHAPTER 3 outlines the methodology adopted to achieve the research objectives. It describes the development of the integrated CRITIC-TOPSIS DM framework and the implementation of FEA to evaluate the structural and impact performance of natural fibre composite materials for cap toe shoes applications. The

chapter also details the modelling assumptions and validation procedures to ensure result reliability.

CHAPTER 4 presents and discusses the results obtained from the integrated material selection and performance evaluation framework developed in this study. In alignment with the research objectives, this chapter systematically reports the outcomes derived from the CRITIC-TOPSIS MCDM techniques and the FEA conducted to assess the structural and impact behaviour of the selected natural fibre composite materials for cap toe shoes applications. The chapter begins with the presentation of the material ranking results and criterion weighting obtained from the CRITIC-TOPSIS method. This is followed by a detailed discussion of the FEA outcomes, including mesh convergences, stress distribution, deformation response, and impact behaviour. The chapter concludes by identifying key research gaps that justify the integrated FEA and MCDM approach adopted in this study Finally, the chapter synthesises the findings from both approached to support the deliberation and justification of the optimum material selection.

CHAPTER 5 concludes the study by synthesising the principal findings and summarising the key outcomes. It further provides recommendations for future research based on the limitations and insights identified in this work.

This thesis is intended for readers with a foundational understanding of composite materials, MCDM techniques, and engineering analysis, particularly those with an interest in natural fibre composites, finite element analysis simulation, and cap toe shoes design.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

In this chapter, a review of the related information is conducted based on journals, books and internet resources. Generally, the literature review mainly concerns the design construction of cap toe shoes for safety shoe. This includes the type of materials, framework construction, application of framework, conceptual design generation and finite element approach from past inventors. The potential of natural fibre and thermoplastic composites to be used in the cap toe shoes is also discussed in this chapter. At the end of the chapter, a summary of the literature review is provided that emphasises the gaps that exist within the research area and develops the significant contribution of this research, which has been conducted to expand the existing body of knowledge.

2.2 Safety Shoe

To safeguard the employee's feet from all environmental hazards, shoes with increased protection have been developed. There are numerous types of foot injuries, the most common of which are falls caused by sliding, injuries to the toes caused by falling objects, crushing of the toes by heavy vehicles, and penetrating the foot with sharp objects, resulting in internal injuries and severe infections. In occupational contexts, safety shoes are frequently required to comply with workplace-specific safety regulations and are a common piece of personal protective equipment. High mass, a rigid toe cap, a thick protective outer layer, a thick protective midsole, an anti-slip outer sole, electrical isolation, and an enclosing heel cap are common characteristics of safety shoes. All of these factors are intended to prevent foot injuries (Chang et al. 2016). Occupational footwear includes a variety of boots (e.g., safety, combat, and work) and shoes constructed from a variety of materials and worn in an occupational setting. Even within occupations, footwear construction can vary depending on the task at hand. For instance, while military personnel are typically issued leather boots, they may also be provided boots made from a cotton and nylon blend that perform better in humid environments. Certain design requirements (e.g., higher shaft height, toe caps, increased

stiffness) are mandated by these standards to prevent slippage, contact with hazardous materials, and injuries caused by external objects. Given the potential impact of occupational footwear on physical function, it is necessary to ensure that boots are designed to prevent rather than cause injuries. For instance, slips, trips, and falls are a primary cause of injury among military personnel, firefighters, and law enforcement officers.

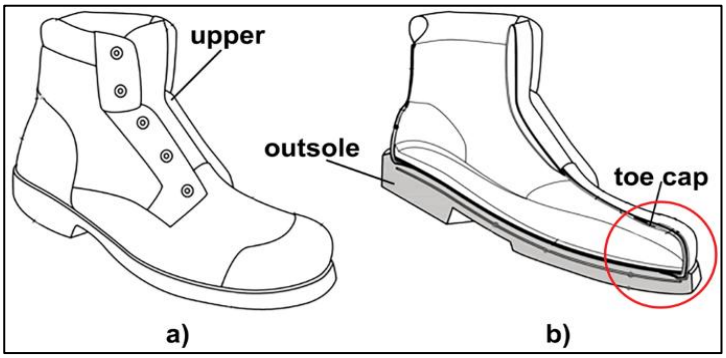


Figure 2.1 Illustration of Safety Footwear (a) Overview of Safety Footwear (b) Cross Sectional View of Safety Foot Wear. (Iacopo Bianchi et al. 2022)

The safety footwear depicted in Figure 2.1 consists of three major components: the outsole, toe cover, and upper. The outsole is the component in contact with the ground and accounts for 50–60% of the shoe's total weight. An anti-perforation insert is typically fabricated from rubber or polyurethane (PU), although ethylene vinyl acetate (EVA) is growing. The upper of the shoe is constructed from leather or technical materials. It accounts for 30–40% of the shoe's total weight. The toe cap is an essential component of safety footwear because it protects the toes; it accounts for 8–15% of the shoe's total weight, depending on the material used in its construction (Iacopo Bianchi et al. 2022). Toe covers can be manufactured from various materials, including steel, aluminium alloys, composites, and polymers.

2.2.1 Cap Toe Shoes

Cap toe shoes are fitted into the front parts of safety shoes to shield a worker's toes from static and impact forces. The normal steel toecap's capacity to absorb impact energy considerably drops when the service temperature is below the zero-ductility temperature of steel, and the heavy cap toe shoes weight may cause workers to become more fatigued. Protective footwear frequently incorporates a cap toe shoes made of

aluminium or high strength steel (Costa, Mendonça, and Peixinho 2016), steel cap toe shoes are often heavy, bulky and "cold", making people less inclined to use them (Kuklane 1997). According to (Arceri et al. 2024) said that weight and inadequate design of the safety footwear may be factors associated footwear discomfort and may potentially explain the observed alterations in gait pattern and foot problems. Therefore, the application of green materials such as natural fibre in the design of the cap toe shoes could be the next solution to the problems relating to its traditional design. In order to address the issues concerning the technical requirements of the design of cap toe shoes and material properties of natural fibre composites, a systematic and structured design approach is required that considers all the basic design elements of mechanical engineering design.

Nowadays, cap toe shoes can be classified in two categories: metallic and non-metallic (I. Bianchi et al. 2022). Many studies concerning the cap toe shoes with standard material can be found in the literature. There is, however, very little for cap toe shoes using NFRC. Composite material has unique characteristics where its material properties depend on its constituents, which are the fibre and matrix. Natural fibre properties vary and are influenced mainly by their chemical composition. The percentage of cellulose, hemicellulose, lignin, pectin and water-soluble compounds varies for different types of natural fibre (Furtado et al. 2014).

In several environments, safety footwear is required as personal protective equipment (PPE) to prevent foot injuries caused by falling objects. To accomplish this, they are outfitted with toe caps designed to safeguard the front of the foot. Cap toe shoes must provide high impact and compressive resistance but must also be as lightweight as possible to meet ergonomic requirements. Employers in industrialised nations must provide PPE to aid in preventing occupational incidents. According to ISO standards, every type of protective footwear is available in three categories: safety, protective, and occupational. Table 2.1 displays the necessary mechanical specifications for safety shoes

Table 2.1
Mechanical Requirements for Safety Shoes

	Category of Safety Shoe	
Toe Cap Requirements	**Safety ISO 20345**	**Protective ISO 20346**
Impact energy (J)	200	100
Compression load (kN)	15	10

Source: Rodrigues et al. 2021

This results in an increase in the total weight of the footwear (Kuklane et al., 1999) . The former is typically fabricated from high carbon steel or aluminium, materials that emphasise mechanical properties but have a high density; this increases the weight of the footwear. Metal cap toe shoes have low production costs and excellent mechanical properties, such as high impact, crack resistance, and low deformation, but are heavy and have poor insulation parameters. Therefore, materials science seeks to develop polymeric materials with higher strength and lower weight than steel while maintaining the appropriate functional properties of cap toe shoes (Kropidłowska et al. 2023). Non-metallic materials, such as composites containing polyester, Polyamide, and epoxy resins with Nano fillers (carbon, aramid, and glass fibres), have increased in recent years (Žukas et al. 2015). Non-metallic materials are highly desirable due to their design flexibility and additional properties, such as electrical insulation, and most importantly, they offer superior thermal insulation compared to metallic cap-toe shoes. Table 2.2 summarises toe cap shoes research published in scientific periodicals based on the authors' experience.

Based on previous studies from 1992 to 2022, research on cap toes shoes shows a clear shift from traditional steel materials to lighter and more advanced composites. Early, studies mainly focused on steel cap toe shoes, emphasising their strength and thermal performance but also noting issues like heaviness and heat conduction. Later works explored alternative such as plastics, aluminium, and high strength steels, aiming to reduce weight while maintaining protection. Recent studies have increasingly used composite materials like carbon fibre, Kevlar, and epoxy-based laminates to improve comfort, impact resistance, and energy absorption. The most recent research even considers environmental sustainability through life cycle assessment. Overall, the trend moves toward lightweight, durable, and eco-friendly designs, suggesting that the future of safety footwear lies in optimise composite materials that balance safety, comfort, and sustainability.

Table 2.2
Summary of Past Studies on Cap Toe Shoes

Title	Material	Author	Year
Thermal aspects of steel toe caps in footgear	Steel	(Kuklane et al. 1999)	1999
A Study on plastic Toe Cap for safety shoes	Plastic	(Cho et al. 2004)	2004
Effect of a Steel Toe Cap on Forefoot Injury Pattern in a Cadaveric Model	Steel	(Kwon et al. 2011)	2011
Innovative Geometric Redesign of Safety Footwear Components Using A Reverse Engineering Approach	Advanced High strength Steels (AHSS),		2016
Study on the impact behaviour of a new safety toe cap model made of ultra-high strength steels	High strength steel	(Costa et al. 2016)	2016
Analysis of Toe Caps for Safety Shoes	Nylon 66 and carbon fibre (CF)	(Kurre 2018)	2018
Kajian Awal Material Pembuat Toe cap (Safety shoes) Menggunakan Metode Elemen Hingga	i. Steel ii. Aluminum iii. Carbon/epoxy iv. E-glass epoxy v. Kevlar/epoxy	(Firmansyah, Anggoro, and Safriana 2021)	2021
Comparative life cycle assessment of safety shoes toe caps manufacturing processes	i. Steel ii. Aluminum iii. Polycarbonate iv. Prepreg	(Iacopo Bianchi et al. 2022)	2022

2.2.2 Cap Toe Shoe Design

The toe caps were modelled according to the dimension of the toe portion of an industrial boot last of size 41 (Limon et al. 2025). Cap toe shoes were 51.3 mm length and 42.5 mm in height on the rear side, and the height gradually decreased on the front side. The maximum width was 93.3. Figure 2.2 shows the dimensions of the cap toe shoes.

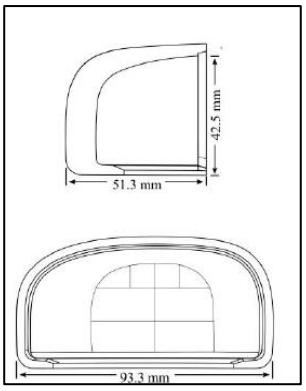


Figure 2.2 Cap Toe Shoe Dimension (Rodrigues et al. 2021)

2.2.3 Emerging Materials for Cap Toe Shoes

The most common material for protective cap toe shoe is steel. Steel protective cap toe shoes are incredibly durable and difficult to damage, but their weight may contribute to worker fatigue (Žukas et al. 2015). Very few attempts have been undertaken to employ natural fibre composites for the same purpose. The most recent and relevant developments on polymeric and hybrid models combining reinforced polyester composites with glass fibre and other advanced compounds for safety toe cap components reported a significant weight reduction, greater than 30 percent, in comparison to standard steel toe caps made of high carbon steel alloys (Costa et al. 2016). Due to their numerous benefits, several natural fibres have been investigated as prospective reinforcements for polymer composites, due to its low cost, availability, and lightweight, among other benefits. Important and unique characteristics of natural composites are their regenerative and biodegradable qualities (Dixit et al. 2017). These materials are environmentally benign, and using green materials in these composites provides an alternative method for managing agricultural waste.

Table 2.3
Comparison of Cap Toe Shoes Based on Steel vs Composite

Type of Material	Advantages	Disadvantages
Steel	i. cheaper price ii. strong iii. already tested iv. many models, sizes, and shapes	i. heavier ii. can be influenced by the ambient temperature iii. Act as conductor
Composite	i. Light and has good durability ii. Not affected by temperature Environment iii. Act as insulation	i. High cost ii. Limited on models, size and shape

Source: Firmansyah et al. 2021

Due to relevant studies on polymeric and hybrid models that fused reinforced polyester composites with glass fibre and other cutting-edge compounds for safety toe cap components, these non-metallic alternatives today weigh less than traditional steel toe caps made of high carbon steel alloys (occasionally paired with specific heat treatments) (Costa et al. 2016). Nevertheless, as deformation responses are stabilised for greater compression and impact stress situations, the primary disadvantage of non-

metallic composites relates to a number of limitations. Table 2.3 compares steel cap toe shoes to composite cap toe shoes.

2.2.4 Natural Fibre Reinforced Composites (NFRC)

Although NFRC have attracted increasing interest in footwear applications, their utilisation in critical components such as cap toe shoe remains notably underexplored (Torres et al. 2023). Conversely, NFRC have been widely adopted in automotive (Babu et al. 2021), aerospace (Gomez-campos et al. 2021), construction (Ntsie et al. 2025), furniture (Ichim, Muresan, and Codau 2024), and marine sectors (El Hawary et al. 2023), owing to their environmentally sustainable characteristics. The increasing adoption of NFRC in new product development is primarily attributed to their lightweight, cost efficient, biodegradable, and no abrasive characteristics, positioning them as viable alternatives to conventional composite material (Elfaleh, Abbassi, Habibi, Ahmad, Guedri, et al. 2023).

Amid increasing emphasis on sustainable production, natural fibre has emerged as attractive reinforcements in polymer composites, valued for their environmental benefits and potential to advance sustainable practices (Palanisamy et al. 2024).. Multiple sectors are increasingly adopting sustainable technologies to balance environmental preservation with socio economic development (Kannan and Gambetta 2025). As illustrated in Figure 2.3, natural fibre is classified into three main categories based on their sources; animal, mineral, and plant. Among these, plant fibre is the most extensively utilised in industry and have been the primary focus of scientific investigation.

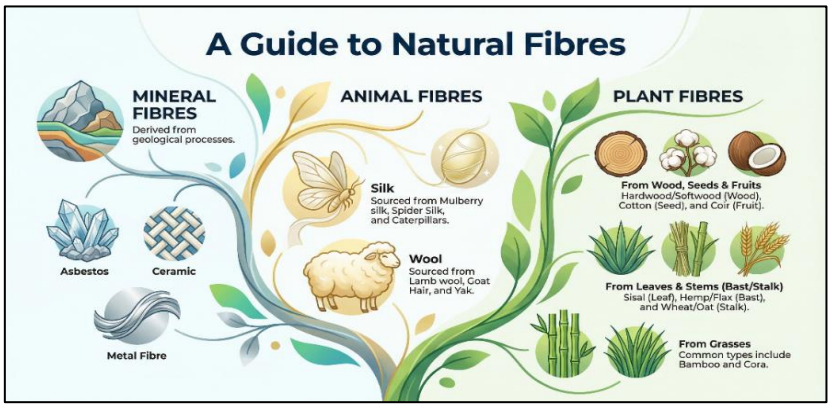


Figure 2.3Classification of Natural Fibres

Natural fibres exhibit several significant advantages over synthetic counterparts, including abundant availability, cost efficiency, low density, favourable modulus to weight ratio, superior acoustic damping, reduced energy requirements during manufacturing, lower carbon footprint, and inherent biodegradability (Nwankwo, Mahachi, and Olukanni 2024). Several studies have demonstrated that natural fibre process distinct advantages over conventional reinforcing fibre such as glass and carbon, particularly in terms of lower cost and reduced energy consumption during processing (Faruk et al. 2012). Conversely, natural fibres exhibit inherent limitations including pronounced variability in physical and mechanical properties, high moisture absorption, reduced durability, lower strength, and constrained processing temperature ranges due to their natural biocomposites structure (Musthaq et al. 2023; Ramful 2024; Shelly et al. 2025). Plant taxonomy fundamentally influences key fibre characteristics such as chemical composition, microstructure, and mechanical behaviour, as well as environmental conditions and extraction methods in which they are grown. Additionally, the properties of cellulose fibre are shaped by the geometry of the fibre cell and the degree of polymerisation (Haidir; et al. 2024). Linear cellulose macromolecules are interlinked through hydrogen bonds and integrated with hemicellulose and lignin, forming a cohesive matrix that imparts rigidity to the fibre. This interwoven structure not only maintains the fibre structural integrity but also binds cellulose within the cell wall (Jarvis 2023; Rao et al. 2023).

Bio based composites offer environmental benefits that depend on the origin of their constituents. A green composite refers to one in which both the reinforcement and matrix are derived from renewable sources, minimising carbon emissions and dependency on petroleum based materials. However, when either the fibre or the matrix is derived is derived from non-renewable sources, the composite, while still partly eco-friendly, cannot be classified as a fully green composite (Ramesh et al. 2022; Zwawi 2021). Natural fibres, derived primarily form botanical, zoological, and regenerative sources, are valued for their biodegradability and environmental benefits, notably their ability to absorb carbon dioxide and release oxygen. In contrast, synthetic fibre is comparatively more expensive. Historically, plant based materials were first applied in residential uses, but in recent years their scope has expanded into diverse sectors including automotive, aerospace, marine, and construction driven by their favourable mechanical, physical, and chemical properties (Puttegowda 2025; Suriani et al. 2021).

Natural fibre composites can be classified as bio composites or fully green composites, depending on whether the polymer matrix is petroleum based or bio based. Bio composites include natural fibre combined with either petroleum derived polymers or bio based polymers. Their biodegradability, however depends largely on the nature of the polymeric matrix. For instance, natural fibre composites reinforced with polypropylene (PP) are nonbiodegradable, whereas those made with polybutylene adipate terephthalate (PBAT) are biodegradable. In contrast, fully green composites consist of natural fibre embedded in renewable, bio based polymer matrices. Yet, even in this category, biodegradability depends on the specific polymer employed, for the example; natural fibre composites reinforced with polylactic acid (PLA) are widely recognised as biodegradable.

Most natural fibres are derived from either plants or animals. The first is primarily composed of cellulose, whereas the latter is predominantly protein-based. Nevertheless, natural fibres are commonly known as vegetable fibres within the composites sector (Peças et al. 2018). Natural fibres are composites that occur naturally and are mainly made up of cellulose fibre that is embedded in a lignin matrix (Satyanarayana et al. 1990). Natural fibres, such as flax, Hemp, Jute, and Coir, are used to create polymer composites, a material with great promise for various uses. Conventional applications of natural fibres include manufacturing yams, ropes, mats, and mattings. Additionally, they are utilised in creating decorative items such as wall hangings, table mats, handbags, and purses. Natural fibre composites contain natural fibres for reinforcement, whereas the binder component comprises polymers. Composite fabrication entails the utilisation of diverse natural fibres, matrix materials, and processing techniques.

Incorporating natural fibre reinforcements in composites has several benefits, including their lightweight properties, easy accessibility, cost effectiveness, non-abrasive qualities, recyclability, low carbon dioxide emissions, biodegradability, and renewable nature (Hughes 2012; Yahya et al. 2023). Plant derived natural fibres, obtained from various parts of plants such as stalks, leaves, stems, fruits, and seeds, possess unique physical, mechanical, and surface qualities specific to each fibre. The growing interest in natural fibre composites is driven by several causes, including its ability to serve as a cost effective and eco-friendly alternative to synthetic fibre reinforced plastics (Pickering, Efendy, and Le 2016). Researchers worldwide have developed biodegradable fibres and polymers to produce innovative bio- composites

that can be alternatives to conventional materials (Lau et al. 2018; Nurul Ain Maidin et al. 2022).

NFRC have been increasingly adopted across multiple industries owing their lightweight, cost effective, and sustainable characteristics. In the automotive sector, plant-based fibres such as flax, Hemp, Jute and door trims, and panels, offering improved fuel efficiency and reduced carbon emissions without compromising performance. Within the building and construction industry, plant fibre composites are incorporated into wall panels, partition boards, and insulation systems due to their excellent sound absorption, thermal insulation, and biodegradability, supporting the principles of green building design. In the furniture and interior product sector, natural fibre composites present renewable and lightweight alternatives to wood and synthetic plastic, aligning with circular economy objectives and modern sustainable design trends. The marine and boat industries have similarly embraced natural fibre composites for non-critical structural parts such as hull panels and decks, valued for their good mechanical strength, corrosion resistance, and reduced environmental impact in aquatic environments. In the packaging and consumer goods sector. Collectively, these diverse applications demonstrate the growing industrial acceptance of NFRC as viable alternatives to synthetic composites, driven by their environmental advantages and potential for sustainable material innovation as shown in Table 2.4.

Table 2.4
Summary of used of Natural Fibre Reinforced Composite

Application Area	**Type of Material**	**Key Description / Purpose**
Automotive	Pant fibre	Widely adopted for reducing weight, cost, and environmental footprint
Building Construction	Plant fibre	Provides strength, sound absorption, and biodegradability in construction
Furniture / Interior products	Natural Fibre	Offers renewable, lightweight, and sustainable design materials
Marine / Boat Structure	Natural Fibre	Used in non-critical structural parts; good mechanical strength and corrosion resistance
Packaging consumer goods	Natural Fibre	Fully renewable and biodegradable; lowest environmental impact
Aerospace	Natural fibre Aerospace	Used in semi-structural parts for sustainability and mass reduction

NFRC reinforced with biodegradable matrices like Polylactic acid (PLA) or polybutylene adipate terephthalate (PBAT) provide fully renewable, biodegradable solutions that mitigate plastic waste and support eco-friendly product innovation. Although their utilisation in aerospace applications remains relatively limited, natural fibre composites are being explored for semi-structural and interior components, where their lightweight nature and energy efficient processing contribute to reduced aircraft weight and lifecycle emissions.

2.2.4.1 Candidate Materials

To identify the most appropriate materials, numerous material criteria have been specified by previous researchers to assist design engineers in the selection process. The density has emerged as a prevalent constraint, since every client demands the product to be lightweight, hence necessitating less force for handling. Aside from that, Young's modulus is a common limitation concerning quality and performance. The selection of natural fibres markedly differs from the selection of other material categories. The chemical qualities of natural fibres correspond to their mechanical properties, influenced by numerous causes. All these factors are necessary to ascertain which natural fibre is most appropriate for the intended purpose. Consequently, Al-Oqla et al. (2015) have defined the material limitations for the selection of natural fibres to be incorporated into composite materials. Each constraint has been clarified comprehensively in the explanation provided in Table 2.5.

Table 2.5
Summary of material constraints for natural fibres

Material constraints	**Description**
Density	To identify lighter natural fibres
Diameter	To identify thickness for processing and composite reinforcement
Length	To identify suitable fibre length for handling, processing, and mechanical reinforcement
Tensile strength	To determine the durability and strength of materials
Young modulus	To measure elastic constant that opposes deformation under applied stress
Elongation at break	To determine the strength and toughness level
Cellulose	To determine the degree of polymerisation and evaluate the mechanical properties
Moisture content	To predict the comparative efficacy of natural fibre under moist environments throughout its lifespan
Hemicellulose	To predict the biodegradation and moisture absoprtion

Source: Al-Oqla et al., 2015

2.2.5 Elastic Properties of Natural Fibre Reinforce Composite

NFRC have gained increasing attention due to their low density, renewability, and environmental advantages compared to synthetic fibre composites. However, the mechanical behaviour of such composites is strongly governed by fibre orientation, fibre matrix interaction, and fibre volume fraction. Among the elastic properties, Young's modulus is a critical parameter for structural performance evaluation and numerical modelling.

The elastic behaviour of the NFRC under longitudinal loading, where the aapplied load is aligned parallel to the fibre direction, is commonly described using the classical rule of mixtures (ROM). Under this loading condition, an iso-strain assumption is adopted, whereby the fibre and matrix experience the same strain. Accordingly, the longitudinal Young'modulus of the composite can be expressed as a linear combination of the fibre and matrix moduli weighted by their respective volume fractions. This formulation has been widely used an upper bound estimate of composite stiffness, particularly for continuous and aligned fibre systems (Graham-Jones and Summerscales 2016; Yasir et al. 2021).

Despite its simplicity, the longitudinal ROM trends to overestimate the stiffness of natural fibre composites. This limitation arises from the inherent variability of natural fibres, including non-uniform, fibre diameter, moisture resistance, and imperfect fibre matrix interfacial bonding. Consequently, several researchers have identified notable differences between moduli predicted using the ROM and those obtained from experimental measurements in natural fibre polymer composite systems, particularly when short or randomly oriented fibres are employed (Phani et al. 2024; Shahid 2025). Accordingly, Equation (2.1) (Muhammad et al., 2024) the longitudinal of the composite can be expressed as:

$$E_C^L = V_f E_f + V_m E_m \tag{2.1}$$

Where E_C^L is longitudinal of the composite E_f and E_m represent the fibre and matrix, respectively, V_f and V_m denote their corresponding, with $E_m + E_m = 1$.

2.3 Multi Criteria Decision Making (MCDM) of Natural Fibre Reinforced Composites

Natural fibres derive from vegetation (cellulose), animals (protein), and geological processes (minerals). Before the discovery of plant fibres, animal fibres were the primary source of clothing. Sheep and bison are among the animals that produce fleece, the first animal fibre known to humankind. Despite being discovered first, animal fibres have been utilised less frequently than plant fibres. There are many different types of natural fibres in the globe. Among these are leaf, seed, bast, core, grass, and reed fibres. They have lower densities than synthetic materials and are generally less expensive to acquire. In addition to being abundant in nature, non-corrosive and biodegradable are additional benefits of natural fibres (Satyanarayana et al. 1990). Early in the twenty-first century, the use of natural fibres began to expand. Among the many applications involved, the automotive industry took it further by producing most of its automobile products, such as seat coverings, floor mats, and door panels, from natural fibres (Sanyang et al. 2016). Fenders made of kenaf/glass hybrid epoxy composite material are also manufactured. Composites are used in various applications in our daily lives to make materials lighter and more durable (Rahman and Ariffin 2022)

Depending on the provenance of the polymers, which can be petroleum based or biobased, natural fibre composites can also be classified as biocomposites or whole green composites. The biodegradability of biocomposites is contingent upon the polymeric matrix employed. Examples include natural fibre-PP-based nonbiodegradable composites and natural fibre-PBAT-based biodegradable composites. Whole green composites: This category comprises natural fibre based composites with polymer matrix made from polymers derived from renewable resources; however, these green composites' biodegradability depends on the polymeric matrix employed. Natural fibre-PLA biodegradable composites, such as natural fibre-bio-nylon nonbiodegradable composites (Mathur 2021). This prospective material type is presently the subject of numerous research developments. NFRC are acquiring popularity for various reasons, including their potential to replace synthetic fibre reinforced plastics at a lower price and with greater sustainability.

MCDM is among the most precise DM techniques. Every decision can be discussed by referencing the DM procedure. As a mental complex process, DM is a

problem solving programme that attempts to determine a desirable outcome by considering various factors (Bonab et al. 2023; Ziemba et al. 2023). This process can be rational or irrational, and it can use implicit or explicit assumptions influenced by various physiological, biological, cultural, and social factors, among others (Hu et al. 2023). All of these factors, as well as the authority and risk levels, can impact the complexity of a DM procedure. Complex DM problems can now be solved with mathematical equations, numerous statistics, mathematics, economic theories, and computer devices that autonomously calculate and estimate the solutions (Akbar et al. 2023). Benjamin Franklin devised one of the earliest studies on MCDM when he published his research on the moral algebra concept. Since the 1950s, several empirical and theoretical scientists have examined the mathematical modelling capability of MCDM methods to provide a framework for structuring DM problems and generating preferences from alternatives. MCDM consists of various methodologies that differ in various aspects, which is discussed in the following sections.

Utilising MCDM techniques in material selection problems has several benefits. First, it offers a systematic and objective strategy for evaluating and ranking materials based on multiple criteria. Second, it assists decision makers in identifying the crucial criteria that have the greatest influence (the highest weight value). Thirdly, it allows decision makers to evaluate and compare the performance of various materials in various circumstances. Lastly, it offers a transparent and structured approach to the DM process, which can aid in building consensus and enhancing communication among stakeholders (Zakeri et al. 2023). Widespread use of MCDM methods in material selection problems for computing the weights of criteria and determining the order of materials. Different academics have proposed various classifications for these two activities. In general, MCDM weighting methods fall into two categories: subjective weighting methods and objective weighting methods. The subjective weighting methods designate criteria weights based solely on human opinions, expectations, and judgements, whereas the objective weighting methods extract the criteria weights from the DM problem's matrix. There are four subcategories of ranking methods, including outranking methods, compromise ranking methods, distance based methods, and pairwise comparison methods. In this case, material selection problems always involve numerous alternatives and criteria, with the reliability of the MCDM methods used to rank the materials decreasing as the number of criteria increases. Utilising MCDM techniques in material selection problems has several benefits:

i. It offers a systematic and objective strategy for evaluating and ranking materials based on multiple criteria;
ii. It assists decision makers in identifying the crucial criteria that have the greatest influence (the highest weight value);
iii. It allows decision makers to evaluate and compare the performance of various materials in various circumstances;
iv. It offers a transparent and structured approach to the DM procedure, which can aid in achieving consensus and enhancing communication among stakeholders.

Previous research has widely utilised MCDM strategies to select materials for various applications. Scant literature examines explicitly the selection of bio composite materials for consumer product applications, such as cap toe shoes. I. Bianchi *et al*,. (2022) demonstrate that approximately 600 million cap toe shoes are discarded annually without the ability to separate them from the shoes. This situation emphasises using carbon fibre prepreg scraps to prevent their disposal in landfills or combustion. These scraps can be used to manufacture certified, lightweight cap toe shoes. The use of plastic technology allows for the replacement of steel cap toe shoes with a plastic cap toe shoes (Cho et al. 2004). These two are the few recent studies published on using cap toe shoes. To the authors' knowledge, no natural fibre has ever been used as a reinforcing component in cap toe shoe designs. Therefore, designers and material engineers would gain advantages from a systematic and structured strategy for selecting materials to aid them in the DM process.

MCDM frameworks have become instrumental in addressing multifaceted real world challenges by evaluating competing alternatives against a diverse set of criterion (Chowdhury and Paul 2020; Sahoo and Goswami 2023). The versatility of these tools is evidenced by their application across disparate domains. For instance, Jharkharia and Shankar (2007) utilised the Analytic Network Process (ANP) to optimise logistics service provider selection, while Stević et al., (2019) applied Simple Addiditive Weighting (SAW) to evaluate supplier sustainability within supply chain.

Beyond industrial logistics, MCDM methodologies have neem adapted for spatial and social analyses. Han et al., (2020) employed Analytical Hierarchy Process (AHP) for road network selection, integrating variables such as point of interest density and global connectivity. More recently, Chan and Ch’ng (2023) demonstrated the sociological utility of TOPSIS by analysing risk factors associated with suicidal ideation among Malaysia university students.

The widespread use of MCDM in academic literature is largely attributes to its ability to support decision makers (DMs) in prioritising critical factors, particularly in contexts requiring technical and economic trade offs are required (Kabir, Sadiq, and Tesfamariam 2014; Mufazzal and Muzakkir 2018). By assigning relative weights to qualitative and quantitative criteria, MCDM provides a mathematically rigorous foundation for measuring preferences and reaching an optimal consensus (Sattar and Ghazwan 2023)

In context of complex group DM, MCDM frameworks are pivotal for ranking alternatives and fostering consensus on strategic objectives among diverse stakeholders (Sotoudeh-Anvari 2023). Despite their robust analytical capabilities, the deployment of these methodologies within public sector organisations remains problematic. Such environments present unique socio political and structural challenges that often impede the integration of formal management ideologies (Maidin et al. 2023). Consequently, MCDM tools are frequently underutilised to the specific organisational DM context or overarching management systems.

2.3.1 Criteria Importance Through Intercriteria Correlation (CRITIC)

The Criteria Importance Through Intercriteria Correlation (CRITIC) method, originally proposed by Diakoulaki et al., (1995), has emerged as one of the most prominent objective weighting frameworks in contemporary MCDM. This methodology is designed to determine attribute weights by analytically extracting the intrinsic information contained within the decision matrix, thereby mitigating the subjectivity inherent in expert based assessment (Pan et al. 2021).

The CRITIC method fundamentally relies on a correlation based technique to determine criteria weights by integrating two fundamental statistical dimensions; the contrast intensity of each criterion, quantified through standard deviations, and the intercriteria conflict, representing by the correlation coefficients across all paired attributes (Pamucar et al. 2022; Žižovic, Miljkovic, and Marinkovic 2020) By synthesising these elements, the method effectively measures the relative importance of criteria based on the spread of data and the degree of redundancy among the variables (Chan and Ch'ng 2023). Step 1 to 5 (Alinezhad & Khalili, 2019; Anand et al., 2022; Diakoulaki et al., 1995) detailed the processes weightage.

Step 1: Construction of the Initial Decision Matrix

The DM process initiates with the formulation of an $m\,x\,n$ decision matrix, A . This matrix serves as the primary data structure, representing the performance of m alternatives relative to n distinct attributes based on empirical data or expert evaluation (Alinezhad and Khalili 2019). The matrix is mathematically expressed as follows:

$$A = \begin{bmatrix} x_{11} & \cdots & x_{12} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{21} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}_{m\,x\,n} \quad ; i = 1,\ldots,m, j = 1,\ldots,n \tag{2.2}$$

where x_{11} denotes the performance value of alternative i_{th} alternative in j_{th} attribute.

Step 2: Normalisation of the decision matrix

In order to normalise the positive and negative attributes of the decision matrix, Equation (2.3) are used, respectively (Alinezhad and Khalili 2019).

$$\overline{x_{ij}} = \frac{x_{ij} - x_j^{worst}}{x_j^{best} - x_j^{worst}} \tag{2.3}$$

Where $\overline{X_{ij}}$ is the normalised score of alternative i with respect to criterion j, x_{ij} is the actual score of alternative i with respect to criterion j, x_j^{best} is the best score of criterion j, and x_j^{worst} is the worst score of criterion j.

Step 3: Calculate the standard deviation of each criterion

Standard deviation of each criterion, s_j, is calculated using Equation (2.4) respectively (Alinezhad and Khalili 2019). Note that $\overline{X_j}$ in Equation (2.3) is the mean score of criteria j and that m is the total number of alternatives.

$$s_j = \sqrt{\left(\frac{\sum_{i=1}^{m} x_{ij} - \overline{x_j}}{m-1}\right)^2} \tag{2.4}$$

where $\overline{X_j}$ is the mean score of criteria j and m is the total number of alternatives.

Step 4: Calculate the Correlation Coefficient

The correlation coefficient among attributes is determined by Equation (2.5) respectively (Alinezhad and Khalili 2019).

$$\rho_{jk} = \frac{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)(x_{ik} - \bar{x}_k)}{\sqrt{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2 \sum_{i=1}^{m}(x_{ik} - \bar{x}_k)^2}} \quad (2.5)$$

Step 5: Calculate the Weight of Attributes

The weights of attributes are determined by Equation (2.6) respectively (Alinezhad and Khalili 2019)

$$w_j = \frac{c_j}{\sum_{j=1}^{n} c_j} ; j = 1, \dots, n \quad (2.6)$$

2.3.2 Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)

TOPSIS method which was proposed by hwang and yoon (Hwang and K Yoon 1981). TOPSIS method is measures the alternative's distance from the ideal best and worst values. The optimal alternative has the shortest distance from the best value and the longest distance from the worst value (Khan and Sahabuddin 2022). This method includes two basic concepts, a positive ideal solution (PIS) and a negative ideal solution (NIS). It ranks the options by calculating the closeness of each alternative to the ideal (Yang, Zhao, and Zhao 2022).

Aires & Ferreira (2019) studies that, the TOPSIS method has been widely used in the literature (Aires and Ferreira 2019). The TOPSIS is a MCDM method commonly employed to assess and rank alternatives by identifying the option closest to the optimal solution and furthest from the negative solution. This method, developed by Hwang and Yoon (1981) (C. L. Hwang and Kwangsun Yoon 1981), posits that the optimal alternatives is characterised by the minimum distance from the PIS and the maximum distance from the NIS (Ertemel, Menekse, and Camgoz Akdag 2023; Hedayati et al. 2022; Kazan and Ozdemir 2014).

TOPSIS method which is the method of MCDM that is most frequently used in studies on material selection (Bilim and Güneş 2023; Ozdemir 2023). An examining material selection for biomedical application in additive manufacturing using TOPSIS approach was published by Jha *et al,*. (2022). On the other hand, Hedayati *et al,*. (2022) investigated a multi objective optimisation of cakes formulated with fig or date syrup

and different hydrocolloids based on TOPSIS. Much research has been done on choosing composite product creation and design materials. Step 1 until 7 (Chodha et al., 2021; Pavić & Novoselac, 2013; Rahim et al., 2018) detailed the processes of the material ranking.

Step 1: Construct the decision matrix (A)

$$A = \left(x_{ij}\right)_{m\,x\,n} = \begin{bmatrix} x_{12} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{2.7}$$

Step 2: Normalise the decision matrix

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^{m} {f_{ij}}^2}} ; j = 1, 2, \dots, m; i = 1,2, \dots, n \tag{2.8}$$

Where $j = 1, 2, \dots, m; i = 1,2, \dots, n$ f_{ij} represents the actual value of the i_{th} value of j_{th} experimental run and R_{ij} represents the corresponding normalised value.

Step 3: Calculate weighted normalised decision matrix

$$v_{ij} = w_i \, x \, r_{ij} \, ; j = 1,2, \dots, j; i = 1,2, \dots, n \tag{2.9}$$

Multiply the columns of the normalised decision matrix in Equation (2.9) by the associated weights to generate the weighted normalised decision matrix.

Step 4: Determine the ideal (A*) and negative ideal (A-) solutions

$$\begin{aligned} A^* &= \left\{\left(\max_i v_{ij} \,\middle|\, j \in C_b\right),\ \left(\min_i v_{ij} \,\middle|\, j \in C_c\right)\right\} = \left({v^*}_j \middle| j = 1, 2, \dots, m\right) \\ A^- &= \left\{\left(\min_i v_{ij} \,\middle|\, j \in C_b\right),\ \left(\max_i v_{ij} \,\middle|\, j \in C_c\right)\right\} = \left({v^-}_j \middle| j = 1, 2, \dots, m\right) \end{aligned} \tag{2.10}$$

Step 5: Calculate the separation measures

The separation measures of each alternative from the PIS and the NIS, respectively

$$S_i^* = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^*\right)^2} \ , j = 1, 2, \dots, m \tag{2.11}$$

Similarly, the distance from NIS is:

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^*\right)^2} \quad , j = 1, 2, \ldots, m \tag{2.12}$$

Where S^* and S^- are distance from the target alternative, i to the worst and best conditions alternatives.

Step 6: Calculate the relative closeness to the ideal solution. The relative closeness of the alternative Pi with respect to RC_i^* is defined in Equation (2.13)

$$RC_i^* = \frac{S_i^-}{S_i^* + S_i^-}, 0 \leq RC_i^* \leq 1, \qquad i = 1, 2, \ldots, m \tag{2.13}$$

RC_i^* = 1 of only if the alternative solution has the best condition; and

RC_i^* = 0 if and only if the alternative solution has the worst condition

Step 7: Rank the preference order.

Rank the alternative according to RC_i^* (i = 1, 2, …, m)

2.3.3 Integrated CRITIC and TOPSIS Method

Despite the documented efficacy of the CRITIC and TOPSIS as individual framework, a significant literature gap persists regarding their integrated application. This study addresses this void by proposing hybrid CRITIC-TOPSIS method, offering designers and material engineers a robust, methodical procedure for complex material selection. By synergising these two methodologies, this study introduces an innovative analytical workflow that eliminates the requirements for subjective inter characteristic comparisons. The objective weighting scheme employed by the CRITIC method eliminates reliance on subjective or heuristic judgements when assigning criterion importance, thereby improving the robustness and consistency of the natural fibre selection process. The integrated framework is well suited for the evaluation of NFRC materials, offering design engineers and manufacturing practitioners a transparent and mathematically sound approach for material optimising during the product design stages.

A comprehensive review of the existing literature, as summarised in Table 2.6, highlights the diverse application sector where the CRITIC-TOPSIS integration has been successfully deployed. While the framework has gained traction in domains such as information technology, financial services, sustainable energy, and heavy industries,

its application within the specialised field of natural fibre selection remains conspicuously underrepresented. The limited number of studies in this area highlights the need for the present research, which aims to formalise the integrated use of MCDM tools to bridge the gap between material science requirements and strategic DM.

Table 2.6
Past Researches on Application Sectors and Domains Covered by CRITIC-TOPSIS

No	Application sectors	References
1	Information technology - Computing software - Smartphone addiction	 (Berdie et al. 2017) (Ertemel et al. 2023)
2	Environmental - Monte Carlo simulation	 (Chen, Shen, and Zhou 2022)
3	Supply chain management	(Abdel-Basset and Mohamed 2020)
4	Sustainable Energy - Green energy - Renewable energy - Value Added Intellectual Capital (VAIC) - Solar PV	 (Lakshmi et al. 2022) (Babatunde and Ighravwe 2019) (Ighravwe and Babatunde 2018; Polcyn 2022) (Hassan, Alhamrouni, and Azhan 2023)
5	Financial and banking - Financial	 (Kazan and Ozdemir 2014)
	Heavy industries - Crane industries - Bridge construction	 (Mohamadghasemi, Hadi-Vencheh, and Hosseinzadeh Lotfi 2020) (Wu et al. 2020)
6	Material - Polymer modified binder (PMB)	 (Slebi-Acevedo et al. 2019)

2.3.3.1 Trends and Insight in CRITIC-TOPSIS Method

Material selection of CRITIC-TOPSIS method in NFRC has not been vigorously explored. This is because there is still a lot more to discover, especially comprehensive studies related to NRFC. The results obviously exposed that the current research patterns NFRC in CRITIC-TOPSIS method is significantly imbalanced. Hence, it is worth to discuss the possibility of contributing to the obvious disparity. The categorisation of newly published works is grounded in the application domain and the methodology utilised in the research, offering insights into contemporary advancements in TOPSIS and its applications. It is inferred from the observation that CRITIC method and TOPSIS method is frequently employed alongside the others MCDM method. The predominant MCDM concerns in these tables relate to aviation, automotive industry

construction, aviation industry, and biodegradable. The tables demonstrate that researchers generally utilised many MCDM techniques to assess the uncertainty associated with various MCDM problems (Zavadskas, Turskis, and Kildiene 2014).

Table 2.7 reveals a trend towards hybrid and fuzzy models, indicating a shift from single method framework to integrated, flexible and robust decisions systems. This integration is particularly relevant in NFRC applications where data may be incomplete, conflicting or subjective. By using objective weighting CRITIC alongside compensatory and non-compensatory models, researchers are able to derive more nuanced and balanced conclusions, ultimately guiding more effective material selection. Importantly, many of the material evaluated, such as biodegradable polymers, natural fibres, and renewable fuels are directly aligned with the scope and focus of bio resources.

The consistent application of CRITIC and its integration with other MCDM methods in assessing materials reinforced the framework credibility and adaptability within the bio resources research domain. The publication demonstrates the expanding role of the CRITIC method as a cornerstone in advanced DM processes for sustainable material evaluation. These studies not only validate the method technical robustness but also provide practical tools for engineers, and policymakers seeking to adopt environmentally responsible materials.

Table 2.7
Selected Publication on CRITIC Method and Others MCDM Method

Authors	**Method**	**Application Area**	**Material**
(Gupta et al. 2021)	CRITIC, WASPAS,	Asphalt Industry	Synthetic Fibre
(Kang et al. 2023)	CRITIC, COPRAS	Biodegradable	Biopolymer
(Singh et al. 2023)	EDAS, CRITIC, ENTROPY, BWM, AHP	Automotive Industry	Natural Fibre
(Kavimani et al. 2024)	CRITIC, WASPAS	Automotive Industry	Natural Fibre
(Mehra, Goel, and Kumar 2024)	CRITIC, MOORA, VIKOR, COPRAS, AHP	Fuel Technology	Renewable Fuel
(Parthasarathy et al. 2024)	CRITIC, EXPROM II	Sustainable Energy	Renewable Energy
(Singh et al. 2024)	CRITIC, MARCOS	Automotive Industry	Natural Fibre
(Balali and Yunusa-kaltungo 2025)	CRITIC, FUZZY EDAS	Construction	Energy Efficiency

Table 2.8 presents two selected studies that demonstrate the integration of the TOPSIS method with other MCDM and intelligent computational methods. These integrations aim to enhance the DM accuracy and objectively in evaluating NFRC materials across different sectors, namely polymer composite engineering and biomedical applications. The consistent appearance of natural fibre as the evaluated material in both studies highlights its growing significance in sustainable product design. The use of natural fibres in both studied reflects a strong alignment with sustainability principle. These fibres, typically sourced from Jute, Hemp, flax, kenaf, or Coir, offer low environmental footprints, biodegradability, and sufficient mechanical properties for various composite and biomedical uses. Their inclusion in high value applications, such as reinforced polymers and biomedical devices, underscores the ongoing shifty form petroleum based to bio resources-based materials.

Table 2.8
Selected Publication on TOPSIS Method Integrated with Others MCDM Method

Authors	**Method**	**Application Area**	**Material**
(Nagamadhu et al. 2023)	PSI, MOORA, COMDAS, VIKOR, TOPSIS	Natural Powder Reinforced Polymer Composite	Natural Fibre
(Keerthiveettil Ramakrishnan et al. 2024)	TOPSIS, GRA, ANN,	Biomedical	Natural Fibre

In the methodological terms, the integration of TOPSIS with other tools such as PSI, VIKOR, ANN, and GRA enhances the precision, adaptability, and multidimensionality of DM processes. These combinations allow for both deterministic evaluation and intelligent learning form empirical or simulation data.

Table 2.9 provides a comprehensive Overview of selected publications that have applied the CRITIC method in conjunction with the TOPSIS method. The integration of the two method demonstrates a growing interest in hybrid MCDM tools for material selection and performance evaluation. The studies reviewed span a wide range of application areas including the automotive industry, energy production, aviation, food packaging, construction, manufacturing, and home appliances. This diversity indicates the flexibility and robustness of the CRITIC-TOPSIS approach in addressing complex decision problems across disciplines.

In the automotive sector, the method has been employed to assess materials such as synthetic glass fibre and natural fibre, with a strong emphasis on sustainability and lightweight properties. Similarly, in aviation and manufacturing industries, natural fibres are frequently evaluated as a replacement for conventional synthetic materials, aligning with global efforts to incorporate eco-friendly material in engineering design. In the field of renewable energy, (Almeida et al. 2024) employed a highly integrated framework combining CRITIC, TOPSIS, EQUAL, AHP, FAHP, and PROMETHEE to support biodiesel feedstock selection. Such methodological complexity underscores the need for accurate, transparent, and comprehensive evaluation processes in critical energy applications.

Table 2.9
Selected Publication on CRITIC Method Integrated with TOPSIS Method

Authors	**Method**	**Application Area**	**Material**
(Alemi-Ardakani et al. 2016)	CRITIC, TOPSIS, ENTROPY	Automotive Industry	Synthethic Glass Fibre
(Anwar 2021)	CRITIC, TOPSIS, EQUAL, ENTROPY, AHP, FAHP, PROMETHE,	Energy Production	Biodiesel
(Bhadra, Dhar, and Abdus Salam 2022)	CRITIC, TOPSIS, AHP	Aviation Industry	Natural Fibre
(Mahajan et al. 2022)	ENTROPY, CRITIC, TOPSIS, VIKOR, PROMETHEE II	Automotive Industry	Natural Fibre
(Mahajan et al. 2024)	ENTROPY, CRITIC, WASPAS, TOPSIS	Food Packaging	Biodegradable Polymer
(Cui et al. 2024)	AHP, CRITIC, TOPSIS	Construction	Organic Binders
(Rahman et al. 2024)	CRITIC, TOPSIS	Manufacturing	Natural Fibre
(Ying et al. 2024)	CRITIC, TOPSIS	Home appliance	Medicanal Herb
(Arslane et al. 2025)	CRITIC, TOPSIS	Manufacturing	Natural Fibre

The reviewed studies indicate that CRITIC-TOPSIS has been widely adopted for MCDM particularly in material selection and engineering applications. The automotuve industry appears as one of the most common application areas, as shown in the studies by (Alemi-Ardakani et al. 2016) and (Mahajan et al. 2022). In addition, several recent studies have focused on natural fibres and sustainable materials, reflecting the growing importance of environmentally friendly alternatives in

engineering design and manufacturing. The integration of CRITIC and TOPSIS is significant because CRITIC provides objective criteria weights, while TOPSIS rank alternatives based on their relative closeness to the ideal solution.

However, the reviewed studies also show that researchers ofthen combine CRITIC-TOPSIS with other MCDM methods such as ENTROPY, AHP, VIKOR, WASPAS, and PROETHEE to validate and compare ranking outcomes. Although the table demonstrates the broad applicability of CRITIC-TOPSIS, it also reveals that limited studies have applied this approach specifically within certain emerging material domains. Therefore, the current study can address this gap by applying CRITIC-TOPSIS to support systematic and objective material selection.

Despite the increasing use of CRITIC-TOPSIS in various engineering domains, including automotive, aviation, construction, and energy, their direct application to NRFC remains underexplored. Only a small fraction of reviewed publication primarily within last three years focus explicitly on NRFC. Highlighting a significant research gap and opportunity for future contributions. The hybrid integration of CRITIC and TOPSIS method emerges as a powerful decision support framework, particularly well suited for the complex tradeoffs associated with sustainable material selection. The methodology enables balanced DM by accommodating conflicting objectives such as cos efficiency, environmental impact, and performance.

Hence, the previous studies indicate that although CRITIC-TOPSIS has been widely used for material selection and engineering DM, existing approaches remain limited in terms of criteria transparency, robustness testing, and practical validation. Furthermore, many studies focus on ranking alternatives without real industrial implementation factors and sustainability indicators. This creates an opportunity for the present study to apply an improved CRITIC-TOPSIS framework that provides more systematic criteria selection, objective weighting, ranking validation, and practical decision support.

The study not only maps the historical development and current application and CRITIC-TOPSIS but also identifies critical pathways for future research. Notably, there is a need to develop Decision Support System (DSS) incorporating CRITIC-TOPSIS to enhance accessibility and usability for practitioners. Additionally, integrating Life Cycle Assessment (LCA) with CRITIC-TOPSIS frameworks could offer comprehensive tools for assessing environmental trade off in material selection.

Such approaches tools will facilitate more informed, objective, and sustainable DM processes, aligning with broader environmental, social, and governance (ESG) goals.

Figure 2.4 shows, the heatmap analysis highlights a clear temporal distribution of MCDM methods applied between 2020 to 2025. AHP and TOPSIS consistently appear across multiple years, reflecting their established role as foundational tools in DM research. In particular, AHP demonstrates a strong presence in 2022 and 2025, suggesting its continuing relevance for structured pairwise comparison and prioritisation tasks. Similarly, TOPSIS shows an upward trend, reaching its peak in 2025, which may indicate increasing interest in distance based ranking approaches in recent studies.



Figure 2.4 Heatmap of MCDM Methods by Year 2020 to 2025

CRITIC emerges as another prominent method, particularly in 2021 and 2024, where its frequency surpasses most of the other method. This suggests growing attention toward objective weighting schemes that minimise subjectivity in evaluation framework. Entropy, while not as dominant, appears consistently from 2020 through 2024, underscoring its role as a complementary method for information-based weighting.

By contrast, several methods such as Stepwise Weight Assessment Ratio Analysis (SWARA), Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR), an acronym in Portuguese for Interactive and Multicriteria Decision Making (TODIM), Complex Proporttional Assessment (COPRAS), and Measurement of

Alternatives and Ranking according to COmpromise Solution (MARCOS) appear only sporadically, often limited to a single instance within a year. This pattern indicates that while novel or less conventional approaches are being explored, they have not yet achieved widespread adoption in the literature. Their occasional presence, however, reflects a willingness among researchers to test alternative MCDM framework in specific problem domains

Overall, the heatmap illustrates a dual pattern; stability of traditional methods (AHP, TOPSIS, ENTROPY) alongside emerging but less frequently applied method. The persistence of classical approaches reinforces their robustness, while the sporadic adoption of newer methods highlights ongoing innovation and diversification in MCDM research.

Decision makers or design engineers should properly select the right materials in order to meet the standard requirement. There are several tools in MCDM to select the suitable materials like AHP, VIKOR, SAW, reference Ranking Organisation Method for Enrichment Evaluations (PROMETHEE), TOPSIS, Grey Relational Analysis (GRA), TODIM, Weighted Aggregated Sum Product ASsessment (WASPAS), MARCOS, SWARA, ENTROPY, COPRAS and CRITIC.

More than seventy MCDM method have been proposed to support DM, as highlighted by Sun et al. (2014). However, the wide range available methods such as VIKOR, AHP, PROMETHEE, CRITIC and TOPSIS often poses a challenge for design engineers in selecting the most appropriate tool for a given problem. According to Li, Y et al. (2024), the application of unsuitable methods can lead to inconsistent or misleading outcomes, thereby compromising the reliability of the decision process. To address this challenge, aiming to enhance the robustness and credibility of complex decision analyses. Such hybrid approaches not only strengthen trust in the results but also ensure safer implementation in practical contexts by Lu, H et al. (2022). Regardless of the method adopted, the definition of criteria, sub-criteria, and their associated weights remains a critical step in aligning the decision process with industrial requirements by Eisa, A et al. (2023). According to Odu, G (2019), it is important to note that each MCDM method possesses unique strengths and limitations that make it more suitable for particular applications. A comparative Overview of CRITIC and TOPSIS characteristics is presented in Table 2.10.

The advantages and disadvantages of CRITIC and TOPSIS highlight a complementary relationship that justifies their integration in MCDM applications.

According to Ye, F et al. (2023) said, CRITIC provides an objective basis for deriving criteria weights by considering both contrast intensity and inter criteria correlations, thereby reducing redundancy and minimising the influence of subjective bias. However, its reliance on purely statistical measures may overlook contextual knowledge and practical interpretability, which can be critical in real world decision environments.

Table 2.10
Advantages and Disadvantages of CRITIC – TOPSIS Method

Methods	**Advantages**	**Disadvantages**
CRITIC	The method incorporates inter criteria correlation, effectively reducing by down weighting criteria that are highly dependent on others, thereby ensuring more balanced evaluations	By relying exclusively on statistical measures, CRITIC does not incorporate domain expertise or contextual knowledge, which may limit the interpretability and practical relevance of the resulting weights
TOPSIS	It provides a clear and logical ranking of alternatives by measuring their relative closeness to the ideal and anti-ideal solutions, which enhances transparency in decision outcomes	The results are sensitive to the normalisation technique used, and different approaches to normalisation can yield different rankings, potentially introducing methodological bias

On the other hand, López-García, A et al. (2025) said, TOPSIS method in offering a clear and intuitive ranking mechanism based on proximity to ideal and anti-ideal solutions, making the decision outcomes more transparent and practically communicable. According to Bánhidi, Z et al. (2024), its sensitivity to normalisation techniques and dependence on weighting schemes can introduce uncertainty and methodological bias, potentially undermining the robustness of its results.

When these two methods are combined, the limitations of each can be mitigated by the strength of the other. The objective weights produced by CRITIC directly address TOPSIS vulnerability to subjective or inconsistent weighting, thereby improving the reliability and fairness of the ranking process. Simultaneously, TOPSIS enhances the practical utility of CRITIC by translating statistically derived weights into an interpretable ranking of alternatives, which is essential for decision makers.

This integration not only strengthens methodological robustness but also ensures a balance between statistical rigour and practical applicability. Consequently, the CRITIC-TOPSIS hybrid framework is particularly well suited for complex decision

contexts such as engineering design, material selection and sustainability assessment, where objectivity in weighting and clarity in ranking are equally critical.

2.3.3.2 Sensitivity Analysis

Sensitivity analysis plays a crucial role in addressing the concern and ensuring the robustness of the results obtained from CRITIC-TOPSIS method. Therefore, modifying the values by increasing or decreasing the weight of certain criteria while allowing others to remain constant will give varying outcomes of the alternatives ranking and overall final decisions (Więckowski and Sałabun 2023). Furthermore, performing sensitivity analysis allows for observing the consistency of ranking results when selecting the most suitable natural fibres material for cap toe shoes. This analysis allows a deeper understanding of the adaptability of the final ranking to changes in weight assignments (Yoon and Hwang 1995). This study analysed the effect of five different scenarios on performance sensitivity, which was determined using Microsoft Excel. The results were subsequently compared to the initial result.

2.4 Simulation Analysis

Quantifying deformation characteristics, stress-strain distributions, and thermal or fluid gradients under external loading conditions is fundamental to optimising structural integrity. FEA provides a robust computational framework for evaluating complex systems by discretising a continuous domain into a finite number of discrete elements. These elements, interconnected at specific points known as nodes, collectively approximate the behaviour of the entire system. The nodes define the Degree of Freedom (DOF), representing the independent kinematic movements available to the structure. The selection of element types is contingent upon the geometric dimensionality of the original structure for instance, line elements are utilised for one dimensional configuration, whereas triangular or quadrilateral elements are employed for two dimensional representations.

Following the definition of element topology, the corresponding constitutive material models and geometric properties are assigned. The accuracy of the simulation is further governed by the application of rigorous boundary conditions that precisely characterise the system constrains. By specifying the relevant mechanical or thermal loads, a global system of equations is generated and solved primarily for nodal

displacements and reaction forces. These primary variables subsequently facilitate the derivation of secondary unknowns, such as stresses and strains. A significant advantage of this discretisation approach is the generation of localised results at each node, enabling high resolution structural assessment. Modern computational tools, such as Hypermesh, have superseded traditional manual calculations by enabling the efficient solution of large scale matrice. Furthermore, advanced post processing tools have significantly expanded the capacity for result interpretation compare to the analytical methods available in previous decades. The standard FEA workflow is categorised into three distinct phases;

i. Preprocessing – The geometric model developed, and the requisite loads, boundary conditions, and material properties are defined to generate the input file for the simulation.
ii. Analysis – Involves the numerical solver processing this input file to solve the governing equations and generate a comprehensive output dataset.
iii. Postprocessing – Transform these raw numerical results into interpretable visual formats, such as contour plots and stress gradients, allowing for a detailed evaluation of the system's performance.

2.4.1 Impact Testing

Impact is fundamentally defined as the rapid application of an impulsive force to a confined volume of material or a localised structural region. While the qualitative effects of impact are extensively documented, the quantitative analysis of the phenomenon remains a complex challenge in predictive modelling. This is particularly evident when correlating resultant effects with applied forced and intrinsic material properties. The consequences of an impact event range from predominantly elastic responses, where energy is dissipated via thermal, acoustic, or internal mechanisms, to more sever outcomes. These outcomes include permanent plastic deformation, structural damage, complete ballistic penetration, or the fragmentation of either the projectile or the target body.

When evaluating the impact behaviour of NFRCs, it is essential to account for their distinct physiochemical characteristics. These materials are characterised by low density, inherent biodegradability, and renewability, coupled with a high degree of natural abundance (Ilyas et al. 2019). For design engineers, quantifying kinetic energy

absorption during impact testing is a critical requirement for the validation of structural design criteria.

To address this requirement, test engineers employ empirical methods to derive energy values from physical data. An established technique involves the measurement of impact force as a function of displacement. By integrating the area beneath the resultant force displacement curve, the total energy dissipated during the event can be precisely quantified in standard energy units. This integrated approach allows for a rigorous assessment of the toughness of the material and its suitability for load bearing applications in product design.

PE = KE (2.14)

The impact energy was determined using the conversation of mechanical energy principles. As the impactor falls from a height, its gravitational potential energy is transformed into kinetic energy immediately before impact. Hence, the energy is given in Equation (2.14), or mgh = $\frac{1}{2}\ mv^2$ (Lei and Yao 2024), where m = mass, h = drop height, g = acceleration of gravity, and v = velocity at impact, the conservation of energy Equation in Equation 2.15.

$$mgh = \frac{1}{2}\ mv^2 \tag{2.15}$$

The impact velocity is independent of mass. Solving from the conservation of energy Equation above and neglecting drag forces caused by air resistance, velocity is calculated in Equation 2.16 (Hamsho and Al-kroom 2026).

$$v = \sqrt{2gh} \tag{2.16}$$

Some idealised load displacement traces, which could be obtained from machines or software analysis, are shown in Figure 2.5.

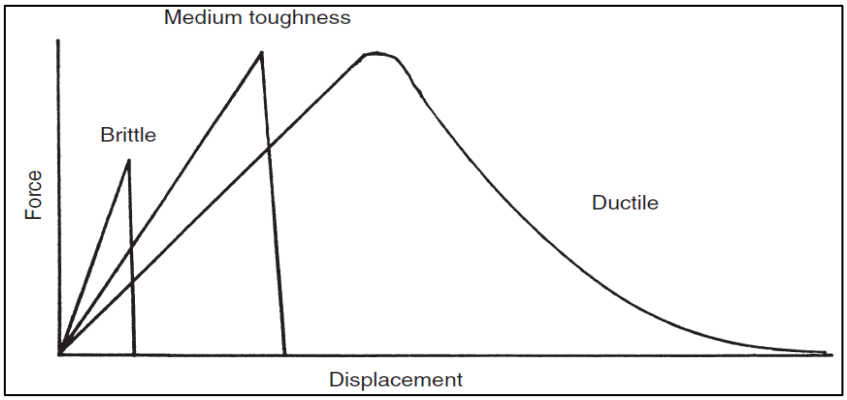


Figure 2.5 Idealised Load Displacement Characteristics for Brittle, Medium Toughness and Ductile Material

2.4.2 Impact Behaviour Analysis

Cap toe shoes used in safety foot wear must withstand an impact loading of 200J, according to ISO standards, the impact behaviour is accessed by measuring the height of a standardised cylinder clay before and after the test. These values must be within a specified clearance range during product validation (Rodrigues et al. 2021).

The impact test method comprises an impact apparatus, incorporating a steel striker, adapted to fall freely on vertical guides from a predetermined height to give the required impact energy calculated as the potential energy (drop test). The hardest parameters for the total safety level were used with a crash energy level of 200J, promoted on the upper toe cap surface, and suitably constrained in the lower region at the time of the attack contact (Peixinho, Costa, and Mendonça 2022).

The FEA of the impact context was developed in order to reproduce, predict and study the cap toe shoes. The FEA software was used and a simulation model set has been defined in common for both different variants made of the corresponding application of the cap toe shoes, which was formulated by three independent parts: the mentioned cap toe shoes body (1:1 scale) that performs the numerical analysis, and its pair of interaction components, formed by a representative striker body – the impaction producer, and the bottom layer for the constrained support of the cap toe shoes.

2.5 Summary

In summary, the review of literature has critically examined the mechanical characterisation of NFRCs, the predictive capabilities of FEA, and the utility of MCDM frameworks. While individual methodologies such as CRITIC and TOPSIS have been widely applied in various engineering sector, the pivotal research gap identified within the extant literature is the absence of an integration CRITIC-TOPSIS framework specifically applied to the material selection of NFRC of cap toe shoes components. Consequently, this study aims to bridge this void by synergising these objective weighting and ranking technique to systematically determine the optimum natural fibre material specifically for cap toe shoes.

However, both the literature and industrial practice indicate that there has been little further innovation regarding the natural fibre material of cap toe shoes. In addition to the sustainable and environmentally friendly characteristics of natural fibre composites that attract manufacturers, a robust design and convincing appearance of the

cap toe shoes is required to attract the end users that actually influence the natural fibre composite market. Apart from that, the literature reviews also revealed that, the type of material that was used, adequate function of the cap toe shoes, subjected forces, potential failure mode and geometry restrictions, which would exhibit its performance. Thus, the identified knowledge gaps found from the literature review highlight significant potential for further investigation into the application of NFRC for cap toe shoes. Table 2.11 summarises previous studies relevant to the current study.

Table 2.11
Summary of Past Research Related to Current Study

	Cap Toe Shoe																				Numerical Software			Material Selection Method						
Author	**high strength Steel**	**AISI 1050 Non-Alloy Steel**	**S235 – Non-Alloy Steel**	**S355– High Strength Low Alloy**	**Structural Steel**	**A36 – High Strength Low Alloy Steel**	**Lexan Polycarbonate**	**Plastic**	**Nylon 66**	**Carbon Fibre**	**Steel**	**Carbon/Epoxy**	**e-glass/epoxy**	**Kevlar/epoxy**	**Green Material**	**Natural Fibre**	**Open Foam ®**	**ANSYS**	**Siemen NX Unigraphics**	**Nasran/Pastran**	**CRITIC**	**Fuzzy AHP**	**TOPSIS**	**EDAS**	**COPRAS**	**GRA**
(Kuklane 1997)										x																
(Cho et al. 2004)							x																			
(Kwon et al. 2011)										x																
(Costa et al. 2016)	x																x									
(Kurre 2018)								x	x	x							x	x								
(Rodrigues et al. 2021)							x									x										
(Firmansyah et al. 2021)											x	x	x						x							
(Kropidłowska et al. 2023)		x	x	x		x	x										x									
(Bhadra and Dhar 2022)															x						x	x	x	x		
(Nurul Ain Maidin et al. 2022)															x										x	
(Zhang et al. 2017)														x								x			x	
Current Study															x		x			x		x				

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

This chapter explains in detail regarding methods used to perform tasks in this study. This includes the methodology flow, which explains in detail about the studies and the troubleshooting steps to obtain the expected result.

In general, this study covers the steps needed to achieve the research objectives of this research mentioned in Chapter 1.3. The study is divided into five stages with each stage dedicated to certain technical tasks associated with the project objective. This is important in defining the research tasks in order to complete this research. In order to construct a framework, the evaluation model was developed through the CRITIC (Criteria Importance Through Intercriteria Correlation)-TOPSIS method. CRITIC method was used to obtaining indicator weight, TOPSIS method were used in order to calculate the total score.

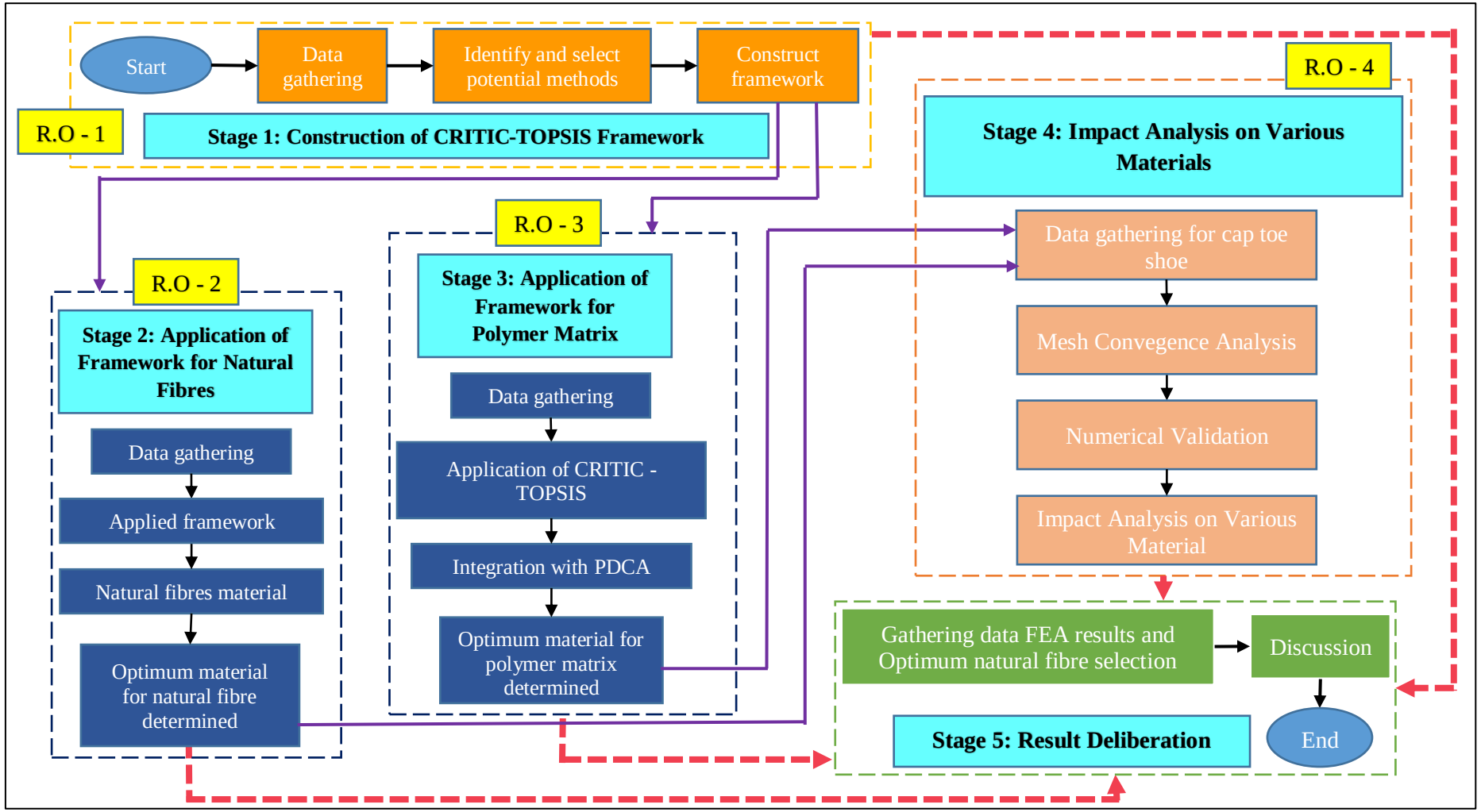


Figure 3.1 Overall Flow of the Study

3.2 Stage 1: Research Framework Development Procedure

Figure 3.2 illustrates stage 1 of the methodology, which focuses on constructing the research framework in alignment with Research Objective 1 (R.O-1). The stage begins with comprehensive data collection, whereby relevant information is systematically gathered from prior scholarly studies, technical reports, and empirical evidence. This process is essential for establishing a robust solid knowledge base, identify gaps in existing approaches, and clearly defining the scope of the present study.

Following data collection, the methodology advances to the identification and selection of potential methods. At this stage, various methodological alternatives are critically evaluated based on their applicability, strengths, and limitations in addressing the research problem. Such comparative assessment ensures that only scientifically rigorous and contextually appropriate methods are considered for integration into the proposed framework.

The final step of this stage involves the construction of the research framework. The selected methods are synthesised into a structured methodological architecture that guides the subsequent phases of the study. This framework operationalises the research objectives while ensuring methodological coherence, reproducibility, and adaptability to the complexity of material selection problems.

Overall, stage 1 establishes a systematic and evidence based foundation for the entire research methodology. By grounding the study in validated knowledge, and informed methodological selection, this stage ensures that subsequent research phases are conducted with clarity, consistency, and scientific rigour.

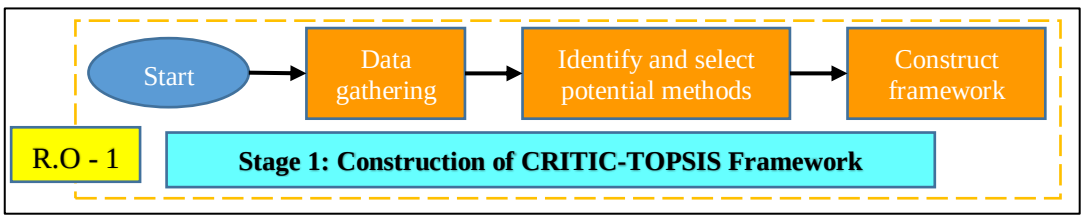


Figure 3.2 Stage 1: Framework Construction Procedure

The methodological framework adopted in this study, as illustrated in Figure 3.3, integrates the CRITIC-TOPSIS method for both validation and practical application in material selection. The integrated framework is designed to ensure methodological robustness, objectivity, and reproducibility in MCDM processes.

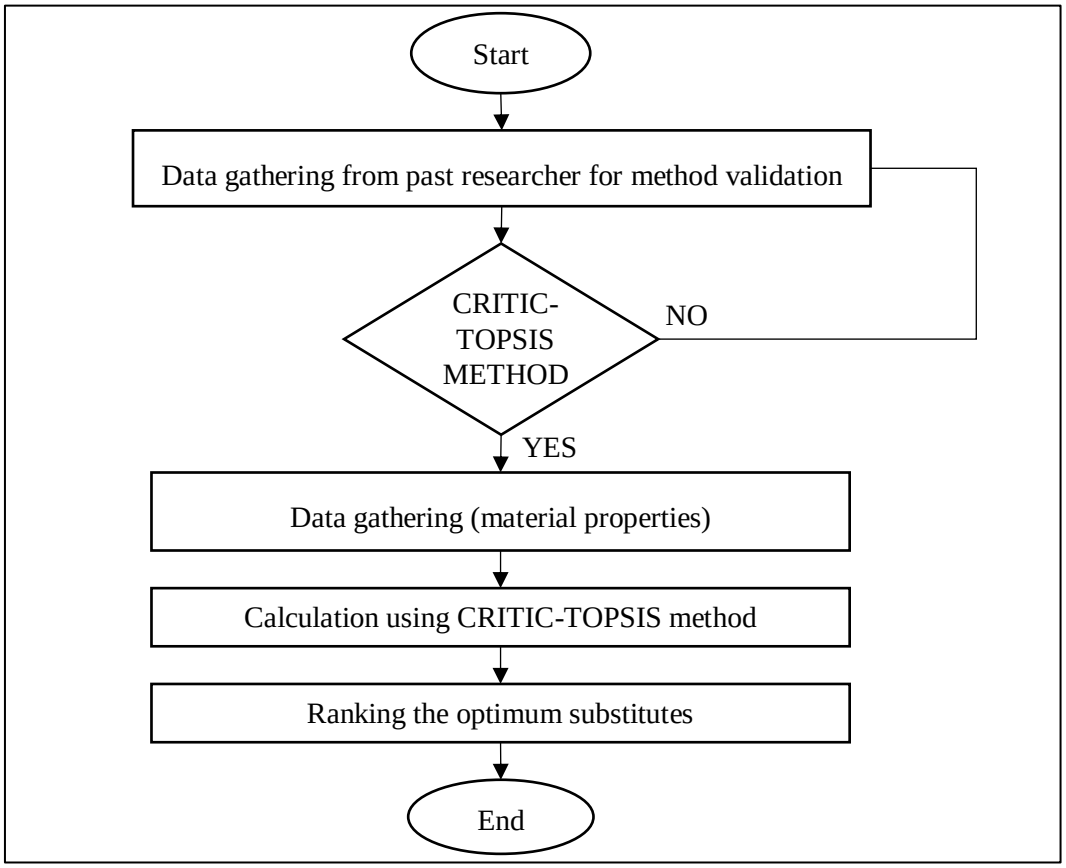


Figure 3.3 Flowchart of the Framework Construction Procedure

The methodology begins with the collection of benchmark datasets from established literature and previous validated studies. These benchmark data serve as a validation platform to assess the suitability and reliability of the CRITIC-TOPSIS method prior to its application to new material selection cases. This preliminary validation step is essential to ensure that the proposed framework yields consistent and credible results. A decision checkpoint is incorporated at this stage to verify the adequacy of the selected method, If the validation outcomes are deemed inadequate, the process iteratively returns to earlier stage for refinement, including further data acquisition and methodological adjustments, thereby enhancing the reliability of the framework.

Upon successful validation, material property data are collected and defined as decision criteria for the material selection problem. The CRITIC method is subsequently employed to determine objective criteria weights. This technique accounts for both the contrast intensity of each criterion, quantified through standard deviation, and the degree of conflict between criteria, evaluated using correlation analysis. The resulting normalised

weights objectively represent the relative importance of each criterion without reliance on subjective judgement.

These objective weights are then incorporated into TOPSIS method. TOPSIS evaluates material alternatives based on their relative distances from the PIS and the NIS. This process involves constructing a weighted normalised decision matrix, computing Euclidean distance, and deriving closeness coefficients to rank the alternatives accordingly. The integration of CRITIC and TOPSIS minimises subjective bias, supports comprehensive multi criteria evaluation, and provides a systematic, transparent, and reproducible framework well suited to addressing complex DM challenges in advanced materials research.

3.2.1 Methodology Procedure for Framework Development

The methodological framework development in this study is structure into four sequential and interdependent phases, as illustrated in Figure 3.4. This systematic and staged approach ensures a coherent validation, and final application. By organising the methodology into clearly defined phases, the framework enhances the reliability, transparency, and robustness of the overall research process.

Phase 1 focuses on the selection and prioritisation of criteria, which establishes the foundational basis for the subsequent analysis. In this phase, critical performance attributes relevant to the material selection problem are identified through comprehensive review of existing literature and domain specific requirements. The key activities involved include, (i) prioritising the performance criteria, (ii) listing and clearly defining each criterion, and (iii) identifying the potential material alternative. This phase ensures that the framework operates using on a well-defined, context appropriate and theoretically grounded set of evaluation parameters.

Phase 2 involves the integration of the CRITIC-TOPSIS methodological procedure, which constitutes the core analytical component of the framework. Initially, the CRITIC method is applied to objectively determine the weights of the selection criteria by quantifying contrast intensity and inter criteria relationships. Subsequently, the TOPSIS method is employed to the ranking of material alternatives based on their relative proximity to the ideal and negative ideal solutions. The combined use of CRITIC and TOPSIS minimises subjective bias and provides a transparent and systematic, MCDM mechanism.

Phase 3 concentrates on the review and validation of the proposed conceptual framework. This phase assesses the internal consistency, methodological integrity, and logical coherence of the developed model, ensuring that the weighting scheme, evaluation procedures, and ranking outcomes function as intended and generate reliable results.

Finally, Phase 4 involves the application of the framework through a case study. This phase demonstrates the practical applicability and effectiveness of the proposed methodology by evaluating and ranking material alternatives under real world condition, thereby confirming its operational validity and relevance.

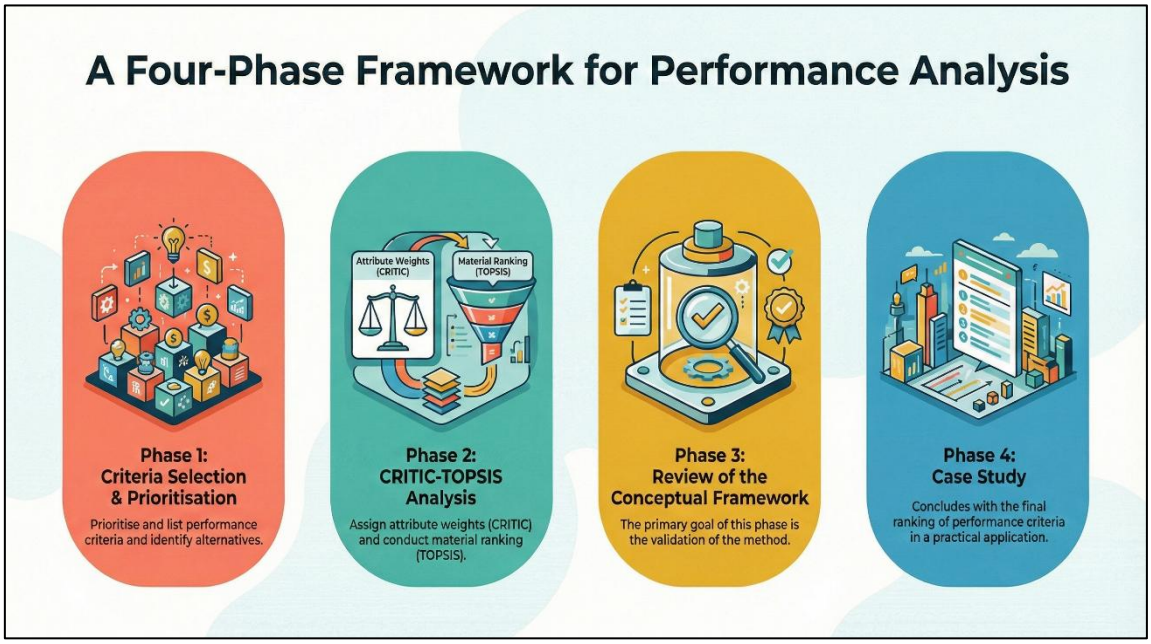


Figure 3.4 Methodological Procedure for Framework Development

The CRITIC-TOPSIS method was selected in this study because the material selection problem for natural fibre reinforced composite cap toe shoes involves conflicting criteria, including mechanical performance, physical characteristics, and moisture related behaviour. The CRITIC method was employed to determine objective criteria weights because it evaluates the importance of each criterion based on contrast intensity, represented by standard deviation, and intercriteria conflict, represented by correlation coefficients. This enables the weighting process to be derived from the decision matrix itself, thereby reducing dependence on subjective judgement. TOPSIS was subsequently adopted to rank the material alternatives because it provides a transparent and mathematically logical procedure by identifying the alternative closest to the positive ideal solution and farthest from the negative ideal solution. The integration of CRITIC and

TOPSIS therefore provides an objective, systematic, and reproducible DM framework for early stage material selection.

Although the CRITIC-TOPSIS framework provides an objective and structured DM procedure, several limitations should be acknowledged. The CRITIC method determines criteria weights based solely on statistical information from the decision matrix and therefore does not directly incorporate expert judgement or contextual industrial preferences. In addition, TOPSIS is sensitive to the normalisation technique and the quality of the input data, which may influence the final ranking of alternatives. The framework also does not directly model physical failure mechanisms such as cracking, delamination, plastic deformation, or localised damage under impact loading. Therefore, FEA was incorporated in the later stage of this study to validate the mechanical response of the selected material under impact conditions.

3.3 Stage 2: Methodological Application of the Framework for Natural fibre Selection in Cap Toe Shoes

Figure 3.5 illustrates Stage 2 of the methodological framework, which emphasises the application of the developed framework in accordance with Research Objective 2 (R.O-2). This stage operationalises the framework constructed in Stage 1 by applying it to the systematic selection of natural fibre materials for cap toe shoes applications. The primary purpose of this stage is to translate the conceptual methodology into practical DM process that supports evidence based material selection.

Subsequently, comprehensive data collection was conducted during which material related information was systematically compiled form reliable literature resources, technical datasheets, and validated experimental studies. This dataset included relevant properties of natural fibres required for composite material evaluation, encompassing mechanical properties (such as tensile strength and young modulus), and physical properties (including density and moisture absorption). Collecting multidimensional data at this stage ensured that the analysis captured both performance related and sustainability oriented considerations relevant to advanced composite design.

Following data acquisition, the process proceeded to the identification and categorisation of natural fibre candidates. Each candidate material is evaluated using the framework established in Stage 1, thereby ensuring consistency in assessment across all alternatives. The criteria and weightings generated through the CRITIC-TOPSIS approach

are applied uniformly, enabling objective comparison among the fibre categories. This structured categorisation facilitated systematic evaluation while accommodating the inherent variability and diversity associated with bio based materials.

The final step in this stage involved determining the optimum material combination for natural fibre reinforced PMC. By applying the integrated CRITIC-TOPSIS framework, the evaluation identified the most suitable pairing of natural fibre and polymer matrix that satisfied the defined DM criteria. This process balanced mechanical performance, sustainability considerations, and practical feasibility. The outcome was a ranked list of material alternatives, from which the optimal combination emerged as the most appropriate candidate for further analysis, validation, and potential industrial application.

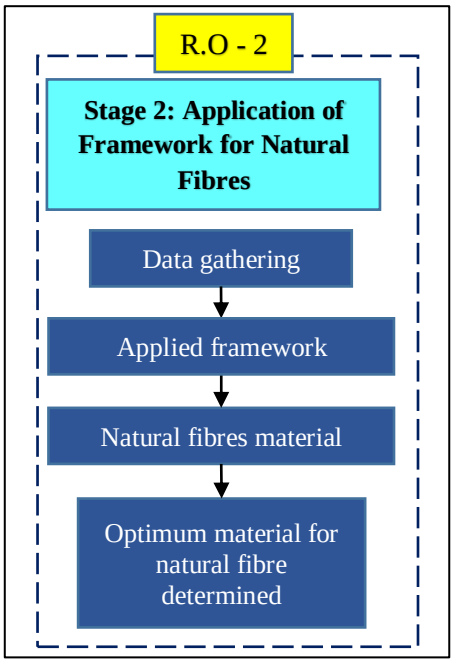


Figure 3.5 Stage 2: Application of the Framework for Natural Fibres Selection

Overall, the implementation of Stage 2 enabled the practical execution of the proposed methodology, effectively bridging theoretical framework development with application oriented material evaluation. By systematically applying the framework, this stage ensured that material selection decisions were transparent, reproducible, and empirically grounded. Consequently, Stage 2 directly supported the achievement of Research Objective 2 by delivering a methodologically rigorous and application oriented solution to the natural fibre selection problem.

The material selection process for natural fibres used in cap toe shoes applications was conducted using a structured, step by step methodological approach. The methodology

adopted in this study employed a hybrid MCDM framework that integrated the CRITIC method with the TOPSIS. This integrated approach was designed to systematically evaluate and identify the most suitable NFRC material for cap toe shoes applications by combining objective, data driven weighting with distance based ranking relative to ideal solutions.

The overall selection process was structured into four main stages to ensure trasnparency, consistency, and robustness in DM. The procedural flow of these stages was illustrated in Figure 3.6, which presented a flowchart depicting the selection of potential materials for cap toe shoes applications.

The first stage involved the definition and structing of the decision problem. At this stage, the reinforcement material selection problem for cap toe shoes was clearly articulated in terms of functional requirements and performance constrains. A comprehensive database of potential natural fibre materials was established based on an extensive literature review and material availability. The shortlisted alternatives included commonly used natural fibres such as Jute, kenaf, Hemp, flax and other relevant bio based reinforcements. Subsequently, a hierarchical decision structure was formulated to reflect the requirements of cap toe shoes and typically included mechanical strength, stuffiness, impact resistance, moisture absorption behaviour, density and other relevant attributes. This structured problem formulation ensured that the evaluation framework was both comprehensive and context specific.

In the second stage, the CRITIC method was applied to determine the objective weights of the decision criteria. This stage began with the construction of a decision matrix, in which the performance of each material alternative was quantified against the defined criteria, to eliminate the influence of differing units and scales, the decision matrix was normalised. The standard deviation of each criterion was then calculated to measure data dispersion, representing the contrast intensity and discriminative power of each criterion. Subsequently, correlation coefficients among the criteria were computed to identify potential redundancy or interdependence. By combining information on variability and intercriteria correlation, the CRITIC method objectively assigned weights to each criterion. This approach ensured that the relative importance of the criteria was derived strictly from the data, thereby minimising subjectivity and avoiding reliance on expert judgement.

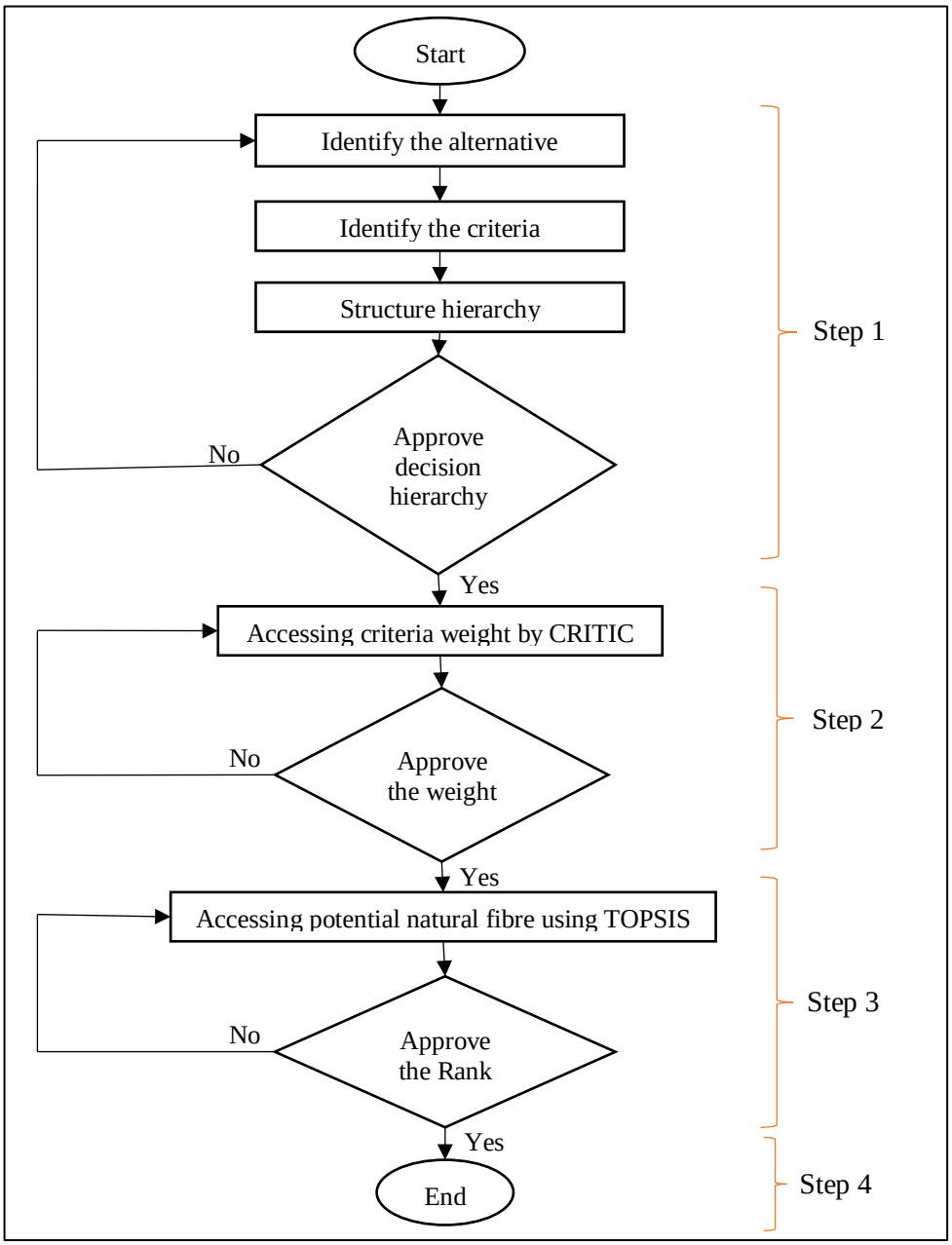


Figure 3.6 Process Flow Chart for Framework Application

In the third stage, the TOPSIS method was employed to rank the material alternatives. The weighted normalised decision matrix obtained from the CRITIC stage served as the input for TOPSIS analysis. The method proceeded by identifying the PIS, which represented the best achievable performance across all criteria, and the NIS, which represented the worst case performance. The Euclidean distance of each material alternative form both the ideal and negative ideal solutions was then calculated. These distances formed the basis for computing the relative closeness coefficient of each

alternative, whereby materials with higher closeness to the PIS and greater distance from the NIS were considered more suitable for the intended application.

The fourth and final stage involved the interpretation of results and DM. Based on the relative closeness coefficients obtained from TOPSIS analysis, all material alternatives were ranked according to their overall suitability. This final ranking provided a transparent, data driven basis for selecting the most appropriate NFRC material for cap toe shoes applications. The structured integration of CRITIC and TOPSIS supported a rational and reproducible material selection process, contributing to sustainable, performance-oriented product design and reinforcing the methodological rigour of the study.

3.3.1 Step 1: Hierarchy Structure Development

3.3.1.1 Problem Definition and Identification of Selection Requirements

The study involved the development of a MCDM model tailored to the specific material requirements of cap toe shoes. Safety footwear constitutes a critical component of PPE across various industrial and occupational environments, where it functioned to reduce foot injuries from falling objects (Firmansyah et al. 2021; Irzmańska 2014; Janson, Newman, and Dhokia 2019) Within this category, cap toe shoes were specifically designed to protect the forefoot region and were therefore required to satisfy stringent performance and safety requirements. Previous studies have reported that cap toe shoes must exhibit high impact and compression resistance while maintaining a low overall weight to ensure ergonomic comfort for the user (I. Bianchi et al. 2022). Consequently, material selection for cap toe shoes component was acquired to account for both mechanical performance and material constraints. Key attributes such as strength, weight, and durability played a pivotal role in ensuring adequate protection, user comfort, and long term functional performance. These considerations necessitated a structured and objective approach to material selection capable of simultaneously addressing multiple, often conflicting criteria.

To address this complexity, the CRITIC-TOPSIS method was adopted as the computational foundation of the proposed MCDM model. CRITIC-TOPSIS method approach was well suited to DM problems that required a compromise among multiple criteria, where shortcomings in one attribute could be offset by favourable performance in others (Pavić and Novoselac 2013). The CRITIC method was employed to derive objective weight for the evaluation criteria by accounting for both data variability and intercriteria

correlation, thereby reducing subjective bias in the weighting process. In contrast, TOPSIS method ranks alternatives based on their geometric proximity to an ideal solution and distance from a NIS. These distances were determined using Euclidean metrics, which quantify the relative closeness of each alternative to the optimal performance state. The PIS represented the best achievable performance for each criterion, while the NIS reflected the poorest attainable values. Owing to its simplicity, computational efficiency, transparency, and strong theoretical basis, the CRITIC-TOPSIS methodology was selected to support robust material evaluation and ranking in this study.

Therefore, twelve characteristics of natural fibres were identified. The criteria were categorised based on the material requirements for cap toe shoes applications, as well as design and production consideration. The primary variables for material selection were identified as strength and weight, with emphasis placed on evaluating the mechanical performance and protective capabilities of natural fibres. In addition, moisture resistance was specified as a key selection criterion. Strength was considered critical because safety footwear primarily aimed to safeguard the user's toes form potential hazards such as falling objects and compression forces (Rodrigues et al. 2021).

The limited water resistance of NFRC has constrained their widespread application, largely due to the inherent moisture absorption behaviour of natural fibres (Wu et al. 2018). Moisture resistance was particularly important for cap toe shoes components, as they were typically enclosed within footwear and frequently exposed to humid conditions. Consequently, the weight of natural fibre was also determined to be a key factor, as it directly influenced the overall mass of safety footwear. This consideration was aligned with consumers demand for lightweight footwear designs that enhance comfort and usability (Costa et al. 2016).

3.3.1.2 Development of Material Alternatives and Database Construction

Twelve natural fibres were chosen selected on their availability of comprehensive and comparable data obtained from multiple sources. The natural fibre candidates were presented in Figure 3.7 according on their respective classifications. Although experimental testing could have been conducted to validate the material properties of the selected natural fibres, this was beyond the scope of the present study due to resource and time constraints.

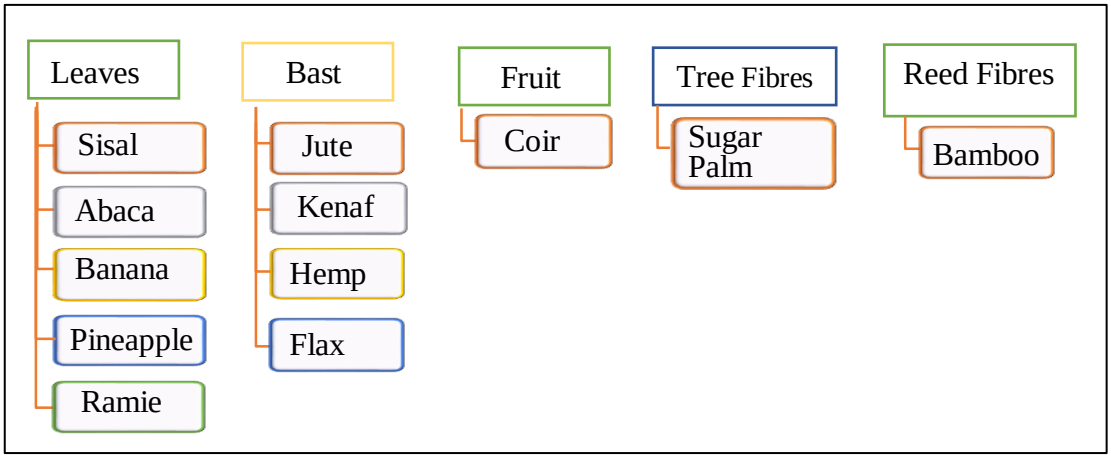


Figure 3.7 Twelve Potential Alternative for Natural Fibres Sorted by Category

Therefore, the required data were obtained from recent and reliable literature sources. Natural composites were characterised by their renewability and biodegradability, making them environmentally sustainable materials with the potential utilise agricultural waste. Accordingly, comprehensive and comparable data for twelve natural fibre alternatives were collected from publications dated 2018 to 2023, as summarised in Table 3.1.

Table 3.1
A Proposed Database of Natural Fibre Alternatives for Cap Toe Shoes Biocomposites from 2018 to 2023

No.	Fibre	Weight			Strength			Moisture Resistance		
		Density (g/cm^3)	**Diameter (µm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemicellulose (%)**
1	Abaca	1.5	10 to 30	4.6 to 5.2	430 to 813	41	2.9	56 to 63	14	21
2	Bamboo	0.6 to 1.1	25 to 88	1.5 to 4	270 to 862	17 to 89	1.3 to 8	26 to 43	11 to 17	11.4
3	Banana	1.35	12 to 30	0.4 to 0.9	721.5 to 910	27 to 32	5 to 6	62 to 64	10 to 11	6 to 19
4	Coir	1.2	7 to 30	0.3 to 3	175	6	15 to 25	45.6	10	0.3
5	Flax	1.38	5 to 38	10 to 65	700 to 1000	60 to 70	1.2 to 3	70 to 80	7	18.6 to 20.6
6	Hemp	1.47	10 to 51	5 to 55	580 to 1110	45	1.6 to 4.5	43	8	17.9 to 22.4
7	Jute	1.23	5 to 25	0.8 to 6	325 to 770	37.5 to 55	1.5 to 3.1	59 to 71.5	12	13.6 to 20.4
8	Kenaf	1.2	12 to 36	1.4 to 11	295 to 930	22 to 60	2.7 to 6.9	53.5	6.2 to 12	21
9	Pineapple	1.5	8 to 41	3 to 8	1020 to 1800	60 to 82	1 to 3	80.5	14	16 to 19
10	Ramie	1.44	18 to 80	40 to 250	915	61.4 to 128	2 to 4	71.09	12 to 17	14 to 16
11	Sisal	1.2	7 to 47	0.8 to 8	507 to 855	9 to 22	1.9 to 3	60 to 77	11	11
12	Ijuk	1.22 to 1.45	221	-	122 to 304.2	2.11 to 5.9	8.9 to 29.9	9.94 to 13.3	43.75 to 52.3	15 to 8.67

Source: Asyraf et al. 2022; Graupner et al. 2019; Sahu and Gupta 2020; Wang et al. 2023

3.3.1.3 Development of the Hierarchical Structure

Initially, the procedure involved developing a hierarchical structure based on the complexity of the material selection problem, as illustrated in Figure 3.8. The hierarchical structure was divided into several sub- problems to facilitate systematic evaluation. At level 1, the primary objective was to select the most suitable material. This objective was further decomposed at level 2 into sub-objectives representing key material criteria including density, diameter, length, tensile strength, Young's modulus, Elongation at break, cellulose, moisture resistance, and hemicellulose. The alternative material options were positioned at level 3. Accordingly, the decision criteria and material alternatives were organised within a hierarchical framework to support structure and transparent DM.

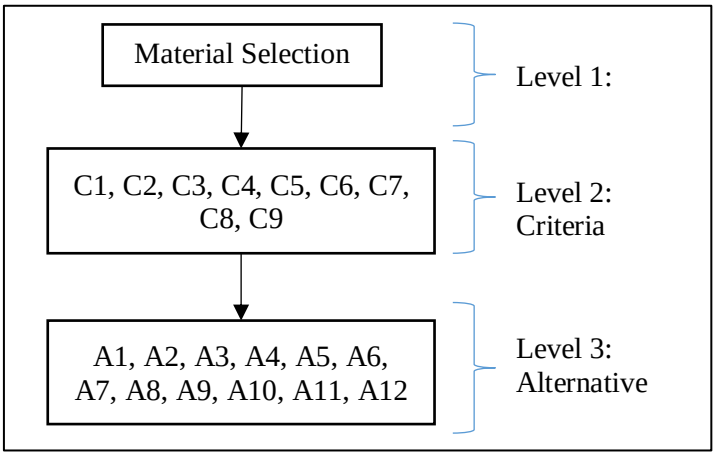


Figure 3.8 The Hierarchy Structure Material Selection for Cap Toe Shoes

3.3.2 Step 2: Determination of Criterion Weights

The CRITIC method was and objective weighting technique based on correlation analysis (Anand, Agarwal, and Aggrawal 2022). It utilised the standard deviations of the normalised criterion values across alternatives, together with the correlation coefficients between all pairs of criteria, to quantify the contrasts intensity and information content of each criterion. Through this formulation, criteria exhibiting greater variability and lower inter criteria correlation were assigned higher weights.

The CRITIC method was widely recognised as one of the most frequently applied objective weighting approached within MCDM. As a correlation based method, it derived criterion importance solely from the statistical characteristics of the data,

thereby enabling an unbiased and data driven determination of criterion weights without reliance on subjective judgement.

3.3.3 Step 3: Performance Evaluation of Material Alternatives

The TOPSIS method was founded on the principle that the optimal alternative exhibited the shortest distance to the PIS and the greatest distance from the NIS. The alternatives were ranked by computing a composite performance index based on their relative distances from these ideal solutions. The TOPSIS method was formulated as a sequence of systematic computational steps, as outlined in the following section. In this study, the TOPSIS analysis was performed to determine the most suitable variant for each natural fibre alternative using Equation (2.7) until Equation (2.13)

3.3.4 Step 4: Selection of the Top Rank Alternative

The overall ranking of the alternative was determined based on their P_i scores, which were calculated using Equation (2.13) and arranged in descending order. The alternative with the highest P_i scores was considered the most optimal solution.

3.4 Stage 3: Application of the Framework for Polymer Matrix Selection in Cap Toe Shoes

Figure 3.9 illustrates Stage 3 of the methodology framework, which emphasised the application of the constructed framework in accordance with Research Objective 3. The stage began with comprehensive data gathering, during which material related information was systematically compiled. This process includes the collection of relevant properties of the polymer matrix, encompassing mechanical, physical, and environmental characteristics essential for polymer matrix design and evaluation.

Once the data had been gathered, the process proceeded to the identification and evaluation of polymer matrix alternatives. Each category was assessed using the framework developed in Stage 1, ensuring that all potential options were evaluated against consistent and scientifically rigorous criteria. This categorisation enabled a structured comparison of materials while accommodating the inherent variability and diversity of bio based resources.

The final step in this stage involves determining the optimum material combination between natural fibre and polymer matrix. Using the integrated framework, the evaluation systematically identified the material pairing that best satisfies the DM criteria by balancing performance, sustainability, and feasibility. The outcome of this process was a ranked set of material alternatives, with the optimal combination identified as the most suitable candidate for further analysis and potential application.

By applying the constructed framework in this manner, stage 3 operationalised the methodology by effectively bridging theoretical development with practical material evaluation. This approach ensured that the research progressed beyond conceptual formulation to deliver empirically grounded insights that directly supported the achievement of Research Objective 3.

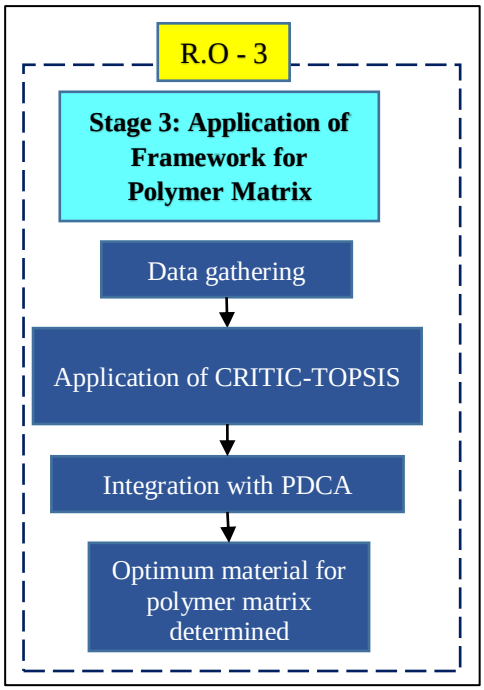


Figure 3.9 Stage 3: Process Flow Application of Framework for Polymer Matrix

The final stage involved optimal design selection and validation, in which the best performing design alternative was identified through MCDM analysis. To ensure continuous improvement, the entire process was embedded within the PDCA cycle, enabling iterative refinement based on performance feedback.

3.4.1 Integration of the CRITIC-TOPSIS Method with the PDCA Cycle

Figure 3.10 illustrates the overall process flow used for polymer matrix selection through the integration of the CRITIC-TOPSIS method and the PDCA cycle. The PDCA cycle was employed in this study to enhance the coherence between planning and execution, as well as to facilitate continuous improvement through the DM process.

For clarity, the overall methodology was structured into in four phases. Phase 1, *Plan*, focused on problem identification and the definition of decision criteria. Phase 2, *Do*, involved the analysis of the collected data. In phase 3, *Check*, the results were examined and evaluated. Finally, Phase 4, *Act*, concluded the workflow by formalising the decision outcomes and implementing the integrated evaluation procedure. Within Phase 4, the workflow consisted of the three main steps:

(a) Generating evaluation criteria weights using the CRITIC method;

(b) Performing the ranking process using the TOPSIS method, and

(c) Combining both algorithm into a single executable script.

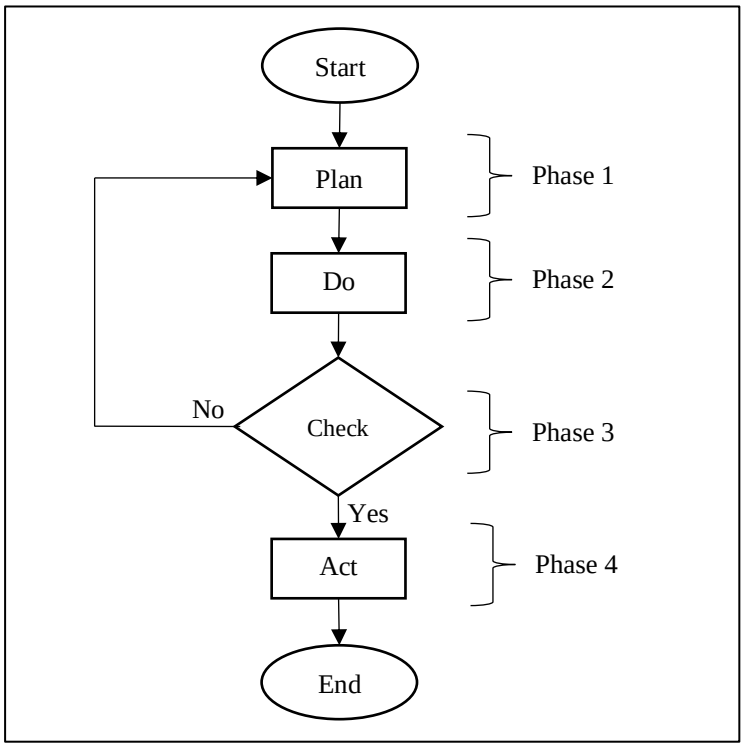


Figure 3.10 PDCA Flowchart for Selection of Polymer Matrix

Phase 1 “Plan”, involved clearly defining the problem and conducting a thorough analysis of the existing situation to identify its root causes. Based on this

understanding, appropriate solutions were formulated and systematically evaluated to determine the most effective options.

Phase 2 “Do”, began once the situation had been comprehensively assessed and an improvement Plan has been established. This phase involved the initial implementation of the planned actions. It was not regarded merely as a trial or pilot exercise; rather, drawing on the comprehensive insights gained during the planning stage, the *Do* phase represents the execution of actions expected to deliver a significant improvement over the existing condition. In addition, this phase provided opportunities for further learning and refinement to inform the subsequent “Check*”* and “Act*”* phases. The selected solutions were implemented sequentially, and those responsible for implementation were required to provide adequate support to relevant stakeholders to ensure that the solutions were properly understood and adhered. All improvements were in accordance with the Plan, and relevant data were systematically collected and documented throughout this phase.

Phase 3 “Check*”*, was the stage which significant learning occurred through the systematic evaluation of the newly implemented processes. By collaborating with relevant personnel to identify which actions were effective, what new insight had emerged, and what adjustments might be required, the team was able to develop a more refined and enhanced Plan. Consequently, the “Check” phase to functioned not merely as a mechanism for identifying issues from the “Do*”* phase, but as a crucial step in elevating the overall process to a higher level of performance. The outcomes of the implemented improvement cycle were assessed to determine the subsequent course of action. If the results indicated that further improvement was required, the process returned to the “Plan*”* phase for refinement. Conversely, when the results were positive, the validated solutions progressed to the “Act*”* phase. It was essential that the new outcomes were systematically compared with the baseline data to determine whether measurable improvements had been achieved and whether the objectives defined in the initial aim statement have been satisfied.

Phase 4 “Act*”* involved preparing the validated solutions for full scale implementation and standardisation, with the potential for extension to the other relevant areas of the organisation. To sustain continuous improvement, the PDCA cycle was intended to be repeated iteratively, enabling the achievement of progressively higher levels of performance over time.

Within this framework, the integrated CRITIC-TOPSIS method served two primary purposes. First, it was employed to identify the optimal configuration for each alternative of (PMC) alternative. Second, it facilitated the selection of potential PMC options were most closely aligned with the primary objective.

3.4.2 Development of MATLAB Code for the CRITIC and TOPSIS Methods

Figure 3.11 presents the process flow chart developed for the creation and validation of MATLAB codes implementing the CRITIC and TOPSIS methods. The flow chart illustrated a structured and systematic sequence of activities undertaken to ensure accurate computation, verification, and seamless integration of both methods within a unified analytical framework. The overall process was divided into three main steps, step 1, development of the CRITIC code. Step 2, development of the TOPSIS code, and step 3, integration of both codes. Each step was designed to incorporate validation procedures to enhance computational reliability and ensure consistency of the resulting output.

The CRITIC was implemented in MATLAB to ensure the accuracy and reliability of the weight determination process. The developed script automated all computational steps, including data normalisation, standard deviation calculation, correlation matrix formulation, and objective weight generation. This automated implementation ensured consistent computation and minimised potential error commonly associated with spreadsheet based calculations.

Similarly, the TOPSIS method was implemented in MATLAB to rank the alternative materials based on their overall performance. The developed MATLAB script automated all stages of the TOPSIS procedure, including normalisation of the decision matrix, weighted normalisation, identification of the positive and negative ideal solutions, computation of separation measures, and calculation of the relative closeness to the ideal solution. This implementation enhanced precision and consistency in the ranking results while significantly reducing the likelihood of manual computational errors.

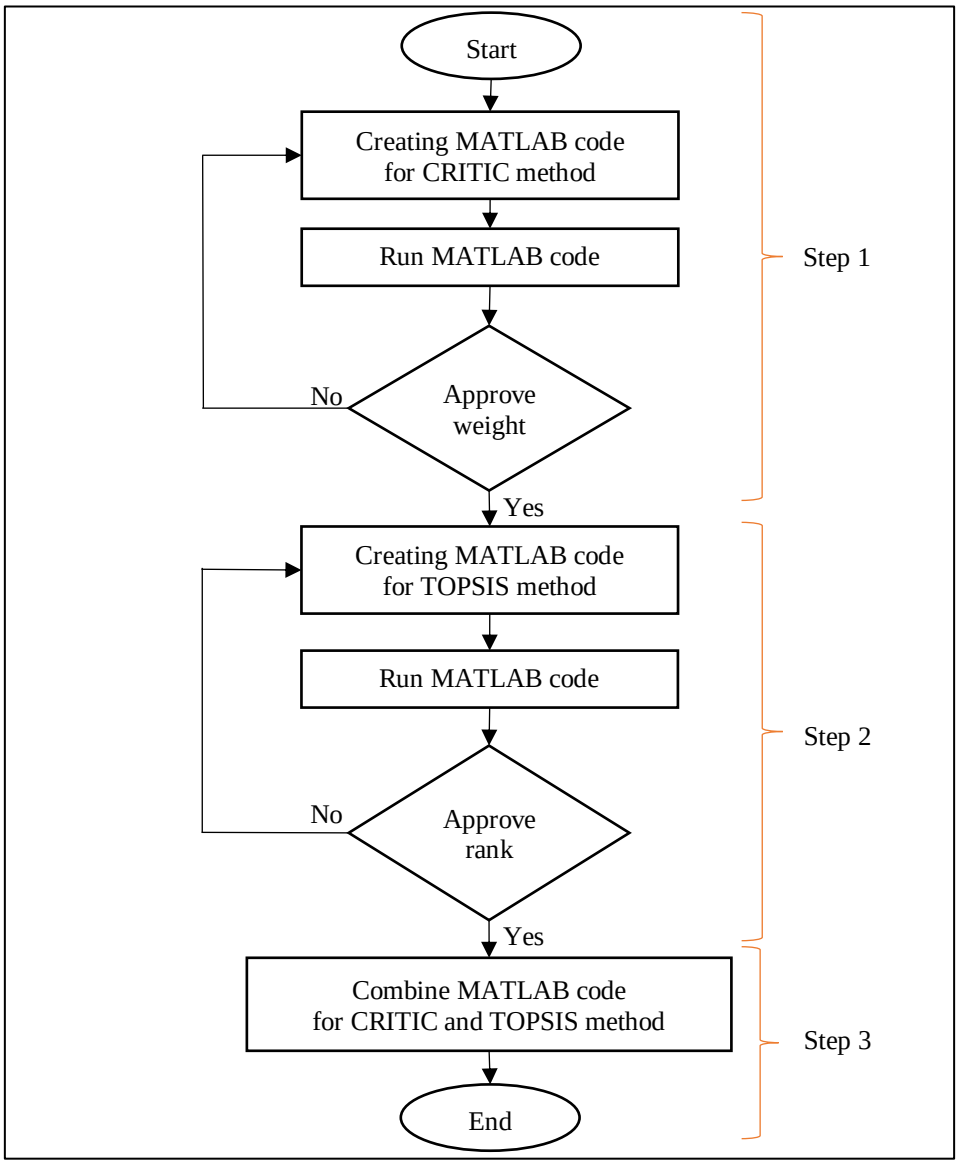


Figure 3.11 Process Flow Chart Creating MATLAB Code for CRITIC and TOPSIS Method

3.4.2.1 Step 1: Development of MATLAB Code for CRITIC Method

The initial step focused on development of the MATLAB code for the CRITIC method, which was employed to objectively determine the relative weight of the evaluation criterion. The algorithm implemented in MATLAB was structured to perform data normalisation, computation of standard deviations, construction of the correlation matrix, and calculation of the CRITIC weights based on contrast intensity and intercriteria conflict.

Following execution of the MATLAB, the computed weights were subjected to a validation procedure, represented in the flow chart as the “Approve weight” decision node. This step involved verifying the logical consistency of the obtained weight, ensuring that higher weights were assigned to criteria exhibiting greater variability and lower redundancy. The MATLAB code developed for the CRITIC method is presented below:

```
% CRITIC Method with Beneficial and Non-Beneficial Criteria
% Author: Hidayat
% Input: Decision matrix (alternatives x criteria)
%        Criteria type: 1 for beneficial, 0 for non-beneficial
% Output: Normalised weights for each criterion
clc; clear;
% --- Input Decision Matrix (Alternatives x Criteria) ---
X = [
   0.39 16.50 26.5 0.17 305.00 1.20 0.40 225.00; % Polyurethane
   0.15 14.00 1.43 0.11 492.50 0.92 0.76 108.50; %Polyethylene
   2.20 65.50 41.50 0.12 60.00 1.20 0.00 302.00; % Polycarbonate
   1.63 33.50 175.24 0.02 58.10 0.90 0.76 149.50; % Polypropylene
   2.00 63.00 45.00 0.30 50.00 1.10 0.00 238.00; % Polyamide
    ];
% --- Define Criteria Type (1 = beneficial, 0 = non-beneficial) ---
criteria_type = [1 1 0 1 1 0 1 1];  % length must match number of columns in X
% --- Step 1: Normalise the matrix using Min-Max normalisation ---
[m, n] = size(X);
Xnorm = zeros(m, n);
for j = 1:n
   if criteria_type(j) == 1  % beneficial
      Xnorm(:, j) = (X(:, j) - min(X(:, j))) / (max(X(:, j)) - min(X(:, j)));
   else  % non-beneficial (cost)
      Xnorm(:, j) = (max(X(:, j)) - X(:, j)) / (max(X(:, j)) - min(X(:, j)));
   end
end
% --- Step 2: Calculate standard deviation for each criterion ---
std_dev = std(Xnorm);
```

```
% --- Step 3: Calculate correlation matrix between criteria ---
R = corrcoef(Xnorm);
% --- Step 4: Compute conflict intensity (1 - correlation) ---
conflict = sum(1 - R, 2)';  % sum of 1 - correlation (row-wise)
% --- Step 5: Compute the information content for each criterion ---
C = std_dev .* conflict;
% --- Step 6: Normalise the information content to get weights ---
weights = C / sum(C);
% Step 7: Rank Alternatives
[~, ranking] = sort(C, 'descend'); % Higher C means better ranking
% --- Output ---
disp('Criteria Weights using CRITIC Method:');
disp(weights);
```

3.4.2.2 Step 2: Development of MATLAB Code for the TOPSIS Method

Following approval of the CRITIC weights, the subsequent phase involved the development of the MATLAB code for the TOPSIS method. The primary objective of this step was to determine the ranking of the alternatives based on their relative closeness to the ideal solution. The objectively derive CRITIC weights were imported into the TOPSIS code to provide a consistent and unbiased hasis for the ranking process.

The MATLAB code was designed to perform normalisation of the decision matrix, apply the respective weights, identify the positive and negative ideal solutions, and compute the relative closeness coefficient for each alternative. The ranking results were than validated through the “Approve rank” decision node to confirm their logical coherence and computational accuracy. In cases where inconsistencies ranking patterns were detected, the code was refined and re executed until satisfactory and stable results were obtained. The MATLAB code developed for the TOPSIS method is presented as follows:

```
clc; clear; close all;
%% Step 1: Input Decision Matrix (Alternatives × Criteria)
 % Tensile Modulus, Tensile Strength, Melt Flow, Water Absorption, elongation at break, Density, chemical resistance, Melting Point
D = [
```

```
0.39   16.50   26.50   0.17   305.00 1.20   0.40   225.00; % Polyurethane
0.15   14.00   1.43    0.11   492.50 0.92   0.76   108.50; % Polyethylene
2.20   65.50   41.50   0.12   60.00  1.20   0.00   302.00; % Polycarbonate
1.63   33.50   175.24  0.02   58.10  0.90   0.76   149.00; % Polypropylene
2.00   63.00   45.00   0.30   50.00  1.10   0.00   238.00; % Polyamide
];
[num_alternatives, num_criteria] = size(D);
% Step 2: Define Criteria Type (1 = Benefit, 0 = Cost)
% --- Define Criteria Type (1 = beneficial, 0 = non-beneficial) ---
% For example, [1 1 0 1 1 0 1 1] means: criteria 1 & 3 are beneficial, 2 is non-
beneficial
criteria_type = [1 1 0 1 1 0 1 1];  % length must match number of columns in X
% --- Step 1: Normalise the matrix using Min-Max normalisation ---
[m, n] = size(D);
Xnorm = zeros(m, n);
for j = 1:n
   if criteria_type(j) == 1  % beneficial
      Xnorm(:, j) = (D(:, j) - min(D(:, j))) / (max(D(:, j)) - min(D(:, j)));
   else  % non-beneficial (cost)
      Xnorm(:, j) = (max(D(:, j)) - D(:, j)) / (max(D(:, j)) - min(D(:, j)));
   end
end
% --- Step 2: Calculate standard deviation for each criterion ---
std_dev = std(Xnorm);
% --- Step 3: Calculate correlation matrix between criteria ---
R = corrcoef(Xnorm);
% --- Step 4: Compute conflict intensity (1 - correlation) ---
conflict = sum(1 - R, 2)';  % sum of 1 - correlation (row-wise)
% --- Step 5: Compute the information content for each criterion ---
C = std_dev .* conflict;
% --- Step 6: Normalise the information content to get weights ---
weights = C / sum(C);
criteria_type = [1, 1, 0, 1, 1, 0, 1, 1];
%% Step 4: Normalise the Decision Matrix
```

```
D_norm = D./ sqrt(sum(D.^2)); % Vector Normalisation
%% Step 5: Compute the Weighted Normalised Decision Matrix
D_weighted = D_norm .* weights;
%% Step 6: Identify Ideal Best and Ideal Worst Solutions
ideal_best = zeros(1, num_criteria);
ideal_worst = zeros(1, num_criteria);
for j = 1:num_criteria
    if criteria_type(j) == 1  % Benefit Criteria
        ideal_best(j) = max(D_weighted(:, j));
        ideal_worst(j) = min(D_weighted(:, j));
      else % Cost Criteria
        ideal_best(j) = min(D_weighted(:, j));
        ideal_worst(j) = max(D_weighted(:, j));
    end
end
%% Step 7: Compute Separation Measures
S_best = sqrt(sum((D_weighted - ideal_best).^2, 2)); % Distance from Ideal Best
S_worst = sqrt(sum((D_weighted - ideal_worst).^2, 2)); % Distance from Ideal Worst
%% Step 8: Compute the TOPSIS Score
C = S_worst ./ (S_best + S_worst);
%% Step 9: Rank Alternatives
[~, ranking] = sort(C, 'descend'); % Higher C means better ranking
%% Display Results
fprintf('\nTOPSIS Results:\n');
disp(table((1:num_alternatives)', C, ranking, ...
    'VariableNames', {'Alternative', 'TOPSIS_Score', 'rank'}));
%% Plot Results
figure;
bar(C);
title('TOPSIS Performance Scores');
xlabel('Alternative'); ylabel('Score');
xticklabels({'Polyurethane ', 'Polyethylene', 'Polycarbonate',
'Polypropylene','Polyamide'}); grid on;
```

3.4.2.3 Step 3: Integration of CRITIC and TOPSIS MATLAB Code

The final step of the process involved the integration of the validated CRITIC and TOPSIS MATLAB codes into a unified computational framework. This integration was undertaken to establish an automated workflow in which criterion weights determination and alternatives ranking were executed sequentially without manual intervention. By combining both methods, within a single codebase, the workflow was fully streamlined, thereby minimising the risk of human error and ensuring consistency and logical coherence across all stages of the analysis.

Within this integrated framework, the process commenced with the CRITIC method, which objectively calculated the relative importance of each criterion based on its variability and degree of correlation with other criteria. The resulting weights were then directly applied in the TOPSIS procedure to evaluates and ranks alternatives according to their relative closeness to the ideal solution. Embedding both methods within the same computational Environment enabled the automatic transfer of CRITIC outputs into TOPSIS, thereby ensuring a continuous, reproducible, and error free workflow. This seamless linkage enhanced computational efficiency by eliminating repetitive tasks and manual data handling.

In addition to enhancing computational efficiency, the integration significantly improved the reproducibility and traceability of the analysis. All computational steps were executed within a controlled MATLAB Environment, enabling the results to be consistently systematic verification and validation of the methodology, thereby increasing confidence in the robustness of reliability of the outcomes.

Furthermore, the integrated CRITIC-TOPSIS framework provided a structured and systematic approach to material evaluation and selection. By maintaining consistent mathematical and logical principles throughout the weighting and ranking processes, the framework ensured that the MCDM procedure remain objective and methodologically sound. This integration ultimately delivered a comprehensive decision support mechanism, capable of producing reliable, reproducible, and logically coherent rankings of alternatives. Consequently, the unified MATLAB implementation represented a critical methodological advancement, supporting efficient and systematic MCDM analyses within analyses within the context of this research.

3.5 Stage 4: Impact Analysis on Various Materials

Finite element models of the cap toe shoes were developed to conduct a parametric study of the material and properties of natural fibre cap toe shoes. A brief Overview of the fundamentals principles of simulation analysis was presented in Chapter 2. The different of cap toe shoes design used in this research are explained in stage 4 shown in Figure 3.12. Necessary changes or improvements performed to the models during the course of thesis are also included in this section.

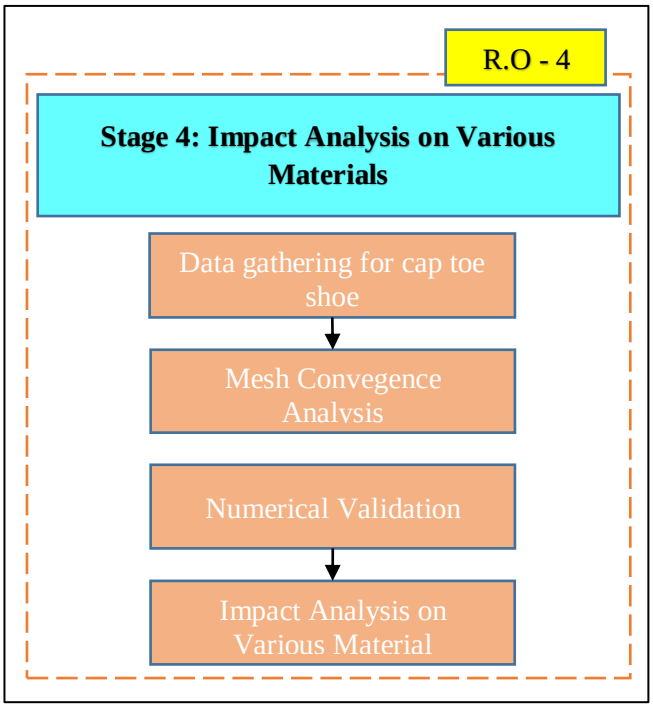


Figure 3.12 Stage 4: Impact Analysis Procedure

Figure 3.13 illustrates the overall procedure of the FEA. The process commenced with the preprocessing stage, which involved the construction of the simulation model and generating of the computational mesh to discretise the geometry. The mesh quality was subsequently reviewed to ensure numerical accuracy and solution stability. Once the mesh satisfied the prescribed quality criteria, the analysis proceeded to the solution stage, during which the solver was executed to compute the structural response based on the defined boundary conditions and material properties.

The postprocessing stage involved interpretation of the simulation results to evaluate the structural response and to verify whether the outcomes satisfied the predefined performance criteria. If the requirements were not met, model refinement

was undertaken and the analysis was repeated. This iterative procedure ensured the accuracy, consistency, and reliability of the finite element analyses performed using ANSYS workbench.

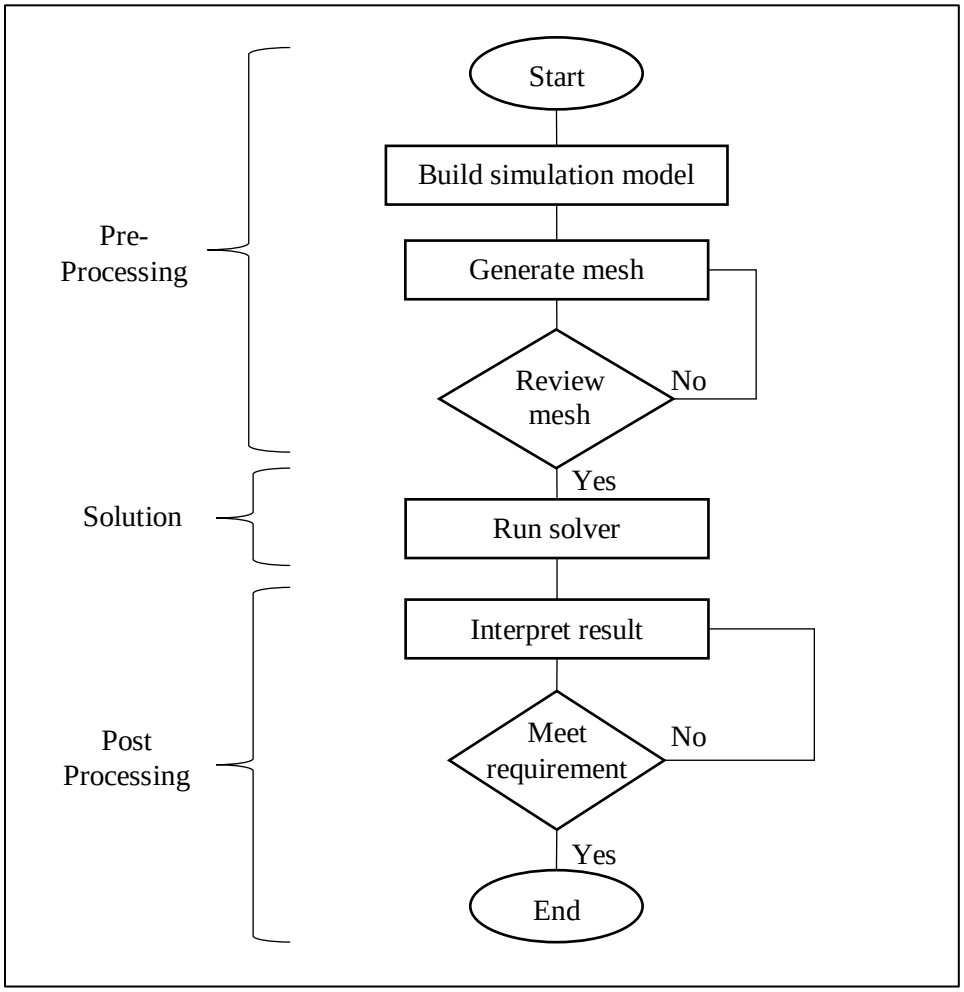


Figure 3.13 Flowchart for Finite Element Approach

3.5.1.1 Mesh Convergence Analysis

A significant limitation of finite element modelling was the sensitivity of the results to mesh size. The use of a finer mesh generally improved the accuracy of predicted results. However, it also increased computational cost, making mesh convergence verification essential. Consequently, convergence analysis was typically performed as an initial step in ANSYS based case studies, enabling the identification of an optimal mesh size that balanced numerical accuracy and computational efficiency. The appropriate element size varied depending on the specific problem being analysed. Therefore, the mesh refinement process had to be tailored to each individual case.

Figure 3.14 (a) and Figure 3.14 (b) presents two contrasting mesh densities, illustrating how variations in mesh size influenced the accuracy of the numerical predictions obtained using ANSYS.

During the convergence study, the mesh was progressively refined until further refinement resulted in negligible changes in the quantities of interest. This approach was widely recognised as critical for ensuring the reliability of numerical results, as it confirmed that the analysis outcomes were not unduly sensitive to element size. By demonstrating mesh convergence, the analysis justified the selected mesh size as sufficiently fine to capture the underlying physical behaviour within an acceptable error margin, while remaining coarse enough to maintain reasonable computational efficiency. Achieving this balance was central to producing trustworthy and practically applicable simulation results.

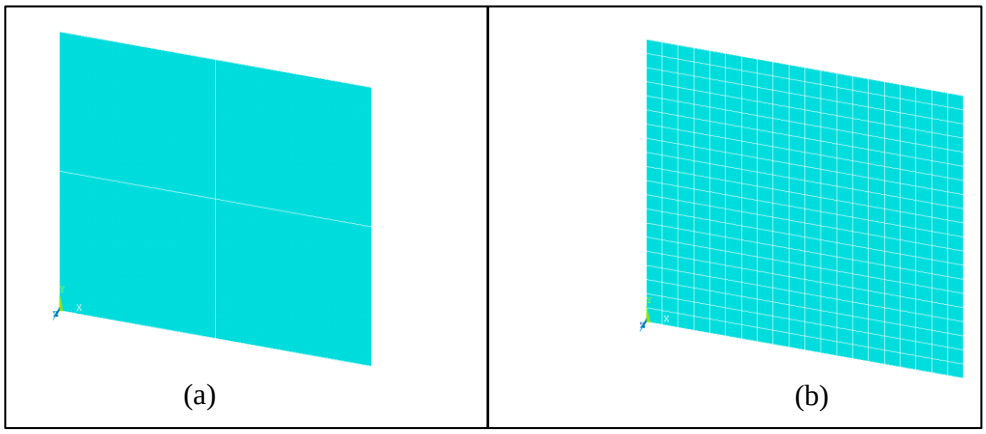


Figure 3.14 (a) Coarse Mesh Size (b) Finer Mesh Size

3.5.1.2 Numerical Validation

Numerical validation was an essential procedure conducted prior to performing any finite element simulation or analysis. This process served to verify that the numerical model developed in the present study was capable of accurately representing the physical behaviour of the system. Numerical validation was achieved by comparing the results obtained from the current model with those reported in previous numerical studies that had been validated through analytical solutions, experimental studies, or established benchmark cases. These reference studies served as reliable benchmarks against which the accuracy and credibility of the developed numerical model were systematically assessed.

By conducting such comparisons, it was possible to evaluate whether the developed numerical model exhibited the expected mechanical response, maintained consistency with established trends, and adheres to fundamental engineering principles. When the underlying physics of the problem are correctly represented across all modelling approaches, the resulting outputs were expected to demonstrate comparable patterns, trends, and magnitudes. Any significant deviation from these reference results indicate potential deficiencies in model formulation, boundary conditions, meshing strategy, or material definitions. Therefore, numerical validation played a critical role in confirming that the numerical model was robust, accurately constructed, and suitable for subsequent parametric investigations or performance evaluations. This validation step ultimately enhanced confidence in the reliability of the simulation results generated throughout the subsequent analysis.

In this research, numerical validation was conducted by comparing the finite element results generated using ANSYS with well-established data reported in previous studies (Kropidłowska et al. 2023). These previously validated findings served as a reliable reference for assessing the accuracy and consistency of the current modelling approach. By adopting a numerical model that had been extensively investigated in existing literature, the present study enabled systematic comparison against recognised benchmark standards. This approach enhances the credibility compared against recognised standards. This approach enhanced the credibility of the simulation results and confirmed that the finite element model was capable of accurately reproducing the mechanical response reported in prior validated investigations.

Table 3.2
Mechanical Properties of the Reference Studies Material

Material	**Density** (g/cm^3)	**Young's Modulus** **(GPa)**	**Poission Coefficient** **(-)**	**Tensilte Strength** **(MPa)**
Lexan	1.19	2.54	0.35	-
AISI 1045	7.85	200	0.30	560-850
S235	7.85	200	0.30	360-510
S355	7.85	210	0.30	510-680
A36	7.80	20.0	0.26	490-620

Source: Kropidłowska et al. 2023

The numerical model was composed of three independents components; a representative striker body, a bottom layer providing constrained support for the cap toe

shoes, and the cap toe shoes model on which the numerical was performed. The analysis model was developed using 3D solid elements. The cap toe shoes model was discretised into tetrahedral structural solid elements with controlled mesh sizing as illustrated in Figure 3.15.

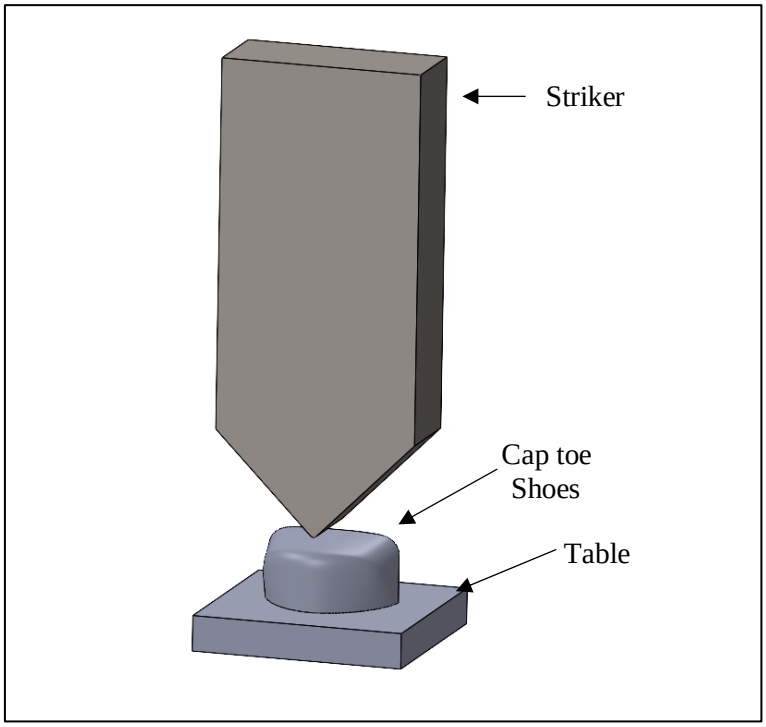


Figure 3.15 Model Setup for Simulation

The finite element model (FEM) boundary conditions included a striker velocity vector immediately prior to impact $V_k = 4480\ mm/s$; a total striker mass of 20 kg, and an initial striker height of = 1075 mm above the cap toe shoes. Gravitational acceleration was applied with a magnitude of $= 9.081\ m/s^2$. In addition, the baseplate was constrained by fully fixing the upper surface with three blocked degree of freedom x-, y-, z- directions.

3.5.2 Elastic Properties of Natural Fibre Reinforced Composite

The composite was assumed to behave as a linearly elastic material under small strain conditions. The fibre and matrix were considered to be perfectly bonded, and the material was treated as homogenous at the macroscopic scale. Equation (1.0) were used to defined the E_C^L. In this study, the fibre volume fraction was varied from 30% to 60%

in order to evaluate the influence content on the density and elastic properties of the NFRC (Kandpal et al. 2022). This range was selected to represented low to moderate fibre loading conditions commonly reported in the literature, while ensuring adequate fibre dispersion and minimising processing related defects such as fibre agglomeration and void formation.

3.6 Stage 5: Result Deliberation

Final phase of this research project involved summarising the key findings derived from the overall study. Figure 3.16 illustrates the structured process used to draw conclusions in relation to the respective research objectives. The key findings encompassed the construction of the proposed framework, the application of framework and the implementation of the finite element approach.

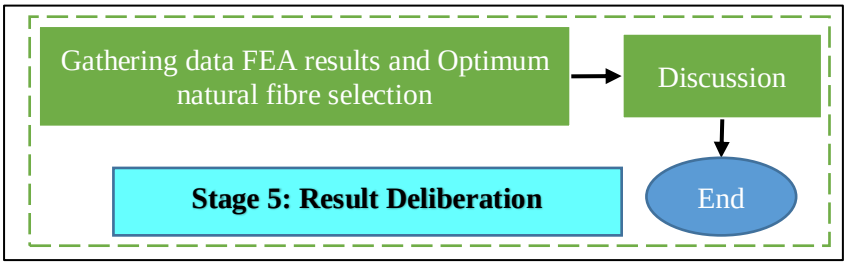


Figure 3.16 Stage 5: Result Deliberation

In conclusion, this chapter presented the overall research strategy adopted for the study. The research was divided into five distinct phases, with specific technical focuses defined for each phase. The research activities were systematically structured in accordance with the project aims and objectives to ensure the coherent execution and successful completion of the research.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

This chapter unveils the results of work highlighted in the previous chapter. Methods presented in the previous chapter were executed accordingly to achieve the objectives of this study. Work was divided into four stages based on the research objectives and scope. The sequence of work was as listed below:

a) Stage 1: To construct a comprehensive framework for prioritising natural fibre composite materials through the CRITIC-TOPSIS MCDM.
   In this stage, the final output a flow of framework was presented.
b) Stage 2: To perform a material selection for natural fibres material in the cap toe shoes design using CRITIC-TOPSIS MCDM approach.

In this stage, the CRITIC-TOPSIS approach was demonstrating in identifying the NFRCs for the intended design

c) Stage 3: To investigate a PMC selection for cap toe shoes design integrating the PDCA with the CRITIC-TOPSIS approaches, and MATLAB coding.

In this stage, the final polymer matrix selection for the intended design is presented using CRITIC-TOPSIS approach, supported by a MATLAB code developed to simplify the DM and calculation process.

d) Stage 4: To simulate finite element models of NFRC cap toe shoes through explicit impact analysis using ANSYS workbench

In this stage, the NFRC cap toes shoes is simulated, with impact analysis using ANSYS workbench in explicit dynamic analysis.

4.2 Stage 1: The Proposed Framework

DM involves defining a decision problem, collecting relevant data, and evaluating alternatives. Edwards (1954) provided one of the earliest comprehensive discussions of DM, emphasising the roles of risk and judgement in decision process. When decisions involve many alternatives, conflicting objectives, or multiple evaluation criteria, MCDM methods are commonly used to improve the structure and transparency of evaluation (Jigeesh, Joseph, and Yadav 2018; Mastura, Sapuan, and

Mansor 2015; Mufazzal and Muzakkir 2018). Such methods are widely applied in environmental and social assessment, technological development, and material selection.

4.2.1 Constructed CRITIC-TOPSIS Method Framework

A key strength of MCDM approaches is their ability to rank alternatives and express decision makers perference in a structured manner. Hwang & Yoon, (1981) introduced the TOPSIS method to support reliable and consistent evaluation of competing options. However, TOPSIS method does not provide an inherent mechanism for eliciting criteria weight or assessing judgemental consistency, which may affect the robustness of the results (Shih et al., 2007). To address this limitation, Diakoulaki et al., (1995) proposed the CRITIC method, which objectively derives criteria weights by considering both contrasts intensity and inter criteria conflict. Therefore, integrating CRITIC with TOPSIS provides a complementary framework for prioritising performance requirements of natural fibre composite materials. By combining objective weight determination with a robust ranking procedure, the CRITIC-TOPSIS framework can enhance the reliability, objectivity, and overall quality of DM outcomes as illustrated in Figure 4.1.

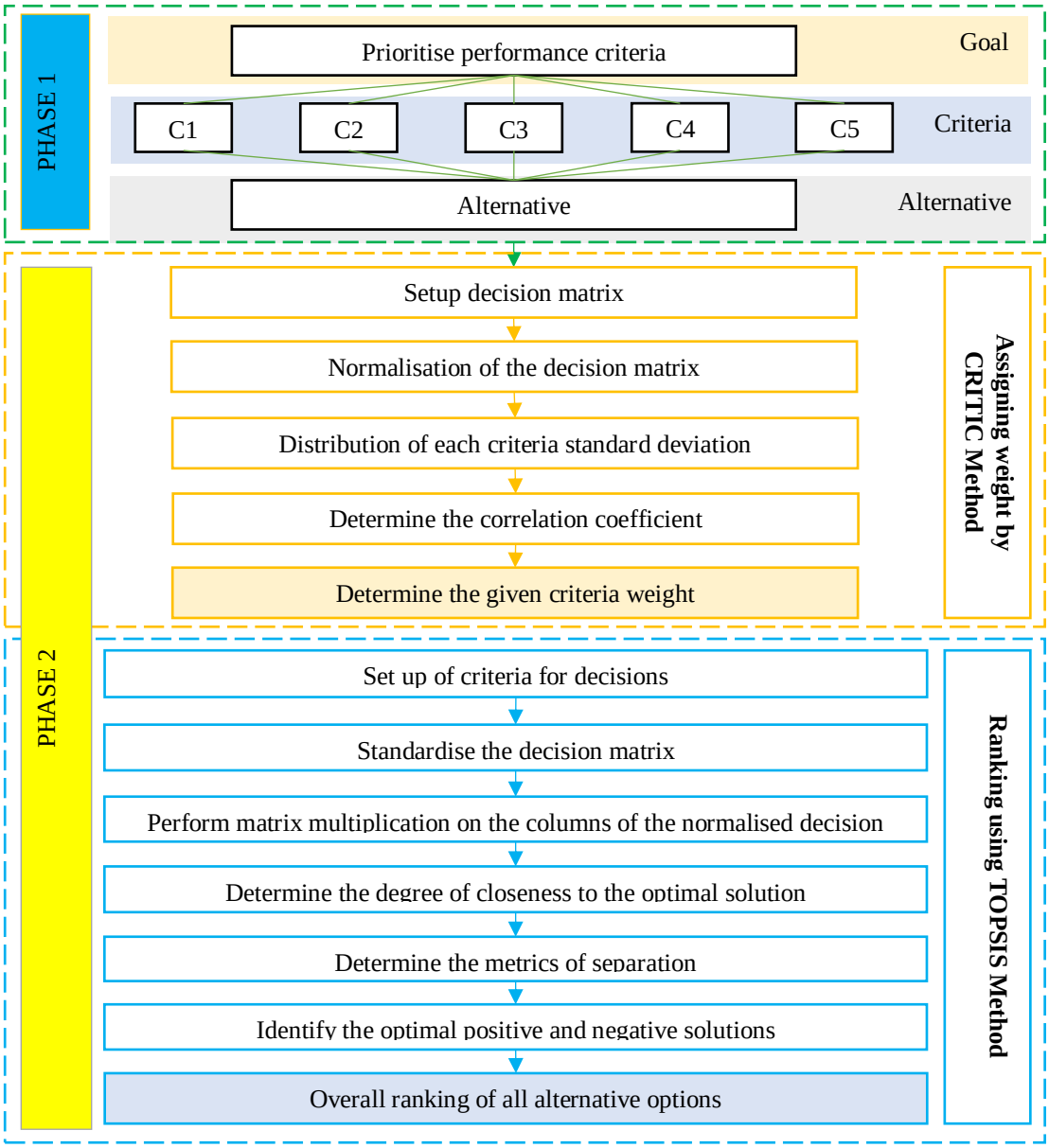


Figure 4.1 The Proposed Framework Model Structure

4.2.2 Conceptual Framework Validation

Prior to its application in the case study, the proposed method was validated by applying it to data reported in previous research. Validation data were obtained from a study conducted by (Saputra, Sitompul, and Sihombing 2018) in which a comparative analysis between the AHP and SAW method was performed. The study investigated a DSS developed to assist in the selection of a department head. Five alternatives were considered, donated as Sample S1 (Muhammad Musa), S2 (Alvin Syahrin), S3 (Noviyanti), S4 (Sofia), S5 (Syaiful Aswad).

In the present study, the same dataset was replicated and analysed using the proposed CRITIC-TOPSIS framework. The resulting were then compared with those obtained using the AHP and SAW methods reported by Saputra et al., (2018). As presented in Table 4.1, the CRITIC-TOPSIS method (current) produced an identical preference order, namely S1>S2>S3>S4>S5 which was consistent with the rankings generated by both AHP and SAW.

The equivalent of the ranking results confirmed the validity of the proposed framework and demonstrated its capability to produce reliable and consistent DM outcomes. Therefore, the CRITIC-TOPSIS based framework was considered suitable for ranking calculations, as it yielded preference structures comparable to those obtained using established MCDM methods such as AHP and SAW.

Table 4.1
Result Ranking for Validation

	MCDM Method					
	CRITIC-TOPSIS (current)		**AHP (Saputra et al. 2018)**		**SAW (Saputra et al. 2018)**	
Alternative	**Value**	**Rank**	**Value**	**Rank**	**Value**	**Rank**
S1	0.997	1	0.274	1	0.993	1
S2	0.629	2	0.241	2	0.883	2
S3	0.435	3	0.193	3	0.707	3
S4	0.237	4	0.158	4	0.578	4
S5	0.015	5	0.135	5	0.490	5

4.2.3 Case Study

In this phase, a case investigation was conducted to rank the performance criteria for cap toe shoes and to assess the suitability and applicability of the proposed framework. The subsequent sections detailed the tasks undertaken in this phase. The performance criteria considered for the evaluation were presented in Table 4.2. Six established alternatives were assessed based on six defined performance criteria,

Table 4.2 presents the selected performance criteria and corresponding properties of six natural fibres, Abaca, Bamboo, Coir, Jute, Kenaf, and Sisal. The six material considered for cap toe shoes applications. The criteria comprised fibre diameter, fibre length, tensile strength, young's modulus, elongation at break, and

cellulose content, which collectively reflected the mechanical performance, reinforcement efficiency, and material suitability under impact loading conditions.

The observed diversity in material attributes confirmed that no single criterion could independently determine the most suitable fibre for cap toe shoes applications. Consequently, an objective and systematic ranking framework was required to balance conflicting performance requirements. These data therefore provided a robust and representative input for thre subsequent CRITIC-TOPSIS analysis, enabling objective weight determination and comprehensive ranking of the natural fibre alternatives.

Table 4.2
Selection of Performance Criteria

	Diameter (µm)	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**
Abaca	20	4.9	621.5	41	2.9	59.5
Bamboo	58	2.75	566	53	4.65	34.5
Coir	18.2	1.65	175	6	20	45.6
Jute	15	3.4	547.5	46.25	2.3	65.25
Kenaf	24	6.2	612.5	41	4.8	53.5
Sisal	27	4.4	681	15.5	2.45	68.5

Source: Biagiotti, Puglia, and Kenny 2004; Luhar et al. 2020; Peças et al. 2018

4.2.3.1 Results of the CRITIC Method

The application of the CRITIC method for selecting performance criteria within the design process was carried out as follows.

Step 1: Construction of the decision matrix.

The process commenced with the formulation of decision matrix. The decision matrix (A), as presented in Table 4.2, comprised all selected performance criteria, which were treated as beneficial criteria. Equation (2.2) was employed to construct the decision matrix (A).

Step 2: Normalisation of the decision matrix

Subsequently, the decision matrix was normalised to eliminate dimensional inconsistencies among the criteria. After determining x_j^{best} and x_j^{worst}, the normalised decision matrix was computed using Equation (2.3), where x_j^{best} represented the maximum value and x_j^{worst} represented the minimum value for each criterion.

Table 4.3
Normalisation of the Decision Matrix

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
Abaca	0.1163	0.7143	0.8824	0.7447	0.0339	0.7353
Bamboo	1.0000	0.2418	0.7727	1.0000	0.1328	0.0000
Coir	0.0814	0.0000	0.0000	0.0000	1.0000	0.3265
Jute	0.0000	0.3846	0.7362	0.8564	0.0000	0.9044
Kenaf	0.2093	1.0000	0.8646	0.7447	0.1412	0.5588
Sisal	0.2791	0.6044	1.0000	0.2021	0.0085	1.0000

Step 3: Calculation of the standard deviation of each criterion.

The standard deviation for each criterion was calculated to quantify the degree of contrast intensity among the alternatives. Using the normalised decision matrix, the standard deviation distribution for each criterion was determine according to Equation (2.4).

Table 4.4
Distribution of each Criteria Standard Deviation

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
Abaca	0.1163	0.7143	0.8824	0.7447	0.0339	0.7353
Bamboo	1.0000	0.2418	0.7727	1.0000	0.1328	0.0000
Coir	0.0814	0.0000	0.0000	0.0000	1.0000	0.3265
Jute	0.0000	0.3846	0.7362	0.8564	0.0000	0.9044
Kenaf	0.2093	1.0000	0.8646	0.7447	0.1412	0.5588
Sisal	0.2791	0.6044	1.0000	0.2021	0.0085	1.0000
STDEV	**0.3655**	**0.3567**	**0.3596**	**0.3963**	**0.3873**	**0.3759**

Step 4: Determination of the correlation coefficient.

The correlation coefficients among the performance criteria were determined to quantify the degree of intercriteria conflict. Pairwise correlation coefficients for all criteria were computed using Equation (2.5), and the resulting correlation matrix was presented in Table 4.5. This coefficient reflected the extend to which criteria were mutually correlated, providing essential input for assessing redundancy and informational overlap among the criteria within the CRITIC framework.

Table 4.5
Pairwise Criteria Correlation Coefficient Values

	Diameter (µm)	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**
Diameter (µm)	1.0000	-0.1914	0.2122	0.4168	-0.1694	-0.7022
Length (mm)	-0.1914	1.0000	0.7488	0.3231	-0.6419	0.4565
Tensile Strength (MPa)	0.2122	0.7488	1.0000	0.5469	-0.9631	0.4401
Young's Modulus (GPa)	0.4168	0.3231	0.5469	1.0000	-0.6690	-0.1933
Elongation at Break (%)	-0.1694	-0.6419	-0.9631	-0.6690	1.0000	-0.4596
Cellulose(%)	-0.7022	0.4565	0.4401	-0.1933	-0.4596	1.0000

Step 5: Determination of criteria weight

The weight W_j of each criterion was determined based on its information content, which incorporates both contrast intensity and intercriteria conflict. After obtaining the standard deviation and correlation coefficients, the information measure c_j for each criterion was calculated using Equation (2.6).

Table 4.6
Determine the Weight of the Selected Criteria

	Major Criteria	C_j.	W_j.
Diameter (µm)	5.4341	*1.9863*	0.1670
Length (mm)	4.3049	7.5357	0.1291
Tensile Strength (MPa)	4.0151	1.4437	0.1214
Young's Modulus (GPa)	4.5756	1.8135	0.1525
Elongation at Break (%)	7.9031	3.0608	0.2574
Cellulose (%)	5.4586	2.0520	0.1725
TOTAL		**11.8920**	**1.0000**

Figure 4.2 illustrated the relative importance of the evaluated performance criteria. The results indicated that the criteria were ranked in the following order; elongation at break > Cellulose > Diameter > Young's Modulus > Length > Tensile Strength. Among these, elongation at break, emerged as the most influential criterion, whereas Tensile Strength was identified as the least influential.

The criteria elongation at break (%) and the cellulose (%) exhibited two highest weights values, indicating that these properties were assigned the greatest importance in the evaluation process. This outcome suggested a stronger emphasis on deformation capability and material composition, which are closely associated with energy absorption and damage tolerance under impact loading conditions. In contrast, Tensile Strength (MPa) recorded the lowest weight, reflecting its relatively lower influence in distinguishing among the selected natural fibre alternatives within the adopted CRITIC framework.

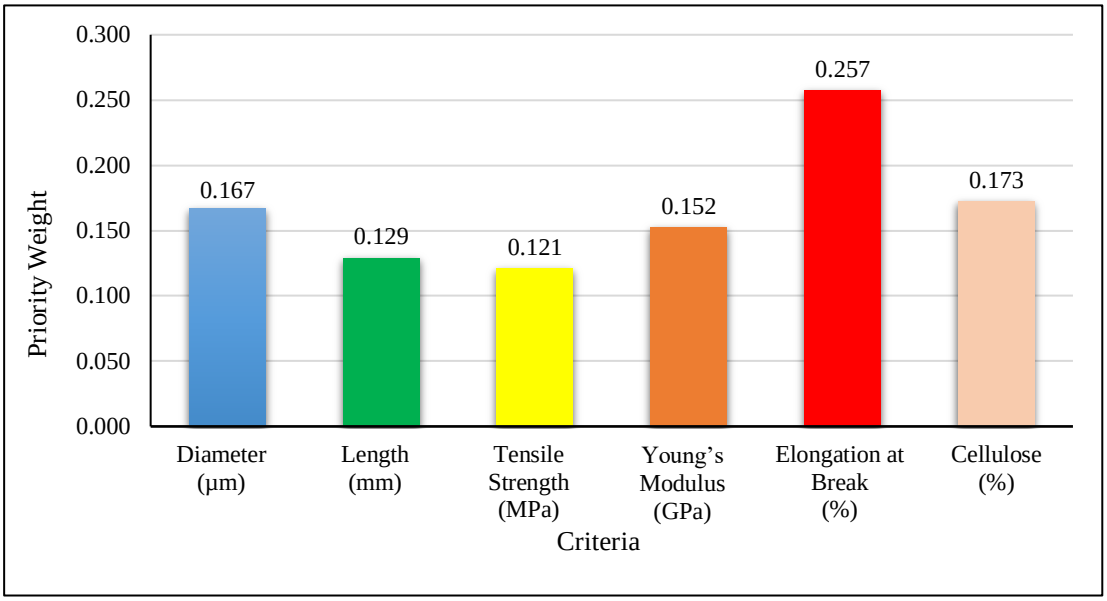


Figure 4.2 Weight for Each Performance Criterion

4.2.3.2 Results of the TOPSIS Method

The TOPSIS method was employed to address the evaluation and selection problem in this study. The implementation of the TOPSIS approach for assessing design performance criteria was conducted as follows.

Step 1: Construction of the criteria for decisions matrix

A decision criteria and alternatives were first established to form the decision matrix (A). The decision matrix, as presented in Table 4.7, was constructed using Equation (2.7) and served as the basis subsequent TOPSIS computations.

Table 4.7
Original Data Matrix

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
WEIGHT	**0.1670**	**0.1291**	**0.1214**	**0.1525**	**0.2574**	**0.1725**
Abaca	20	4.9	621.50	41	2.90	59.50
Bamboo	58	2.75	566	53	4.65	34.50
Coir	18.5	1.65	175	6	20	45.60
Jute	15	3.40	547.50	46.25	2.30	65.25
Kenaf	24	6.20	612.50	41	4.80	53.50
Sisal	27	4.40	681	15.5	2.45	68.50

Step 2: Normalisation of the decision matrix.

The decision matrix was subsequently normalised to remove the influence of differing measurement scales among the criteria. After calculating the sum of squares for each criterion, $\sum f_{ij}{}^2$ the normalised decision matrix values were determined using Equation (2.8).

Table 4.8
Normal Decision Making Matrix

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
WEIGHT	**0.1670**	**0.1291**	**0.1214**	**0.1525**	**0.2574**	**0.1725**
Abaca	0.2664	0.4813	0.4538	0.4425	0.1346	0.4360
Bamboo	0.7726	0.2701	0.4132	0.5720	0.2158	0.2528
Coir	0.2464	0.1621	0.1278	0.0648	0.9281	0.3342
Jute	0.1998	0.3340	0.3997	0.4991	0.1067	0.4782
Kenaf	0.3197	0.6090	0.4472	0.4425	0.2227	0.3921
Sisal	0.3596	0.4322	0.4972	0.1673	0.1137	0.5020

Step 3: Construction of the weighted normalised decision

Matrix multiplication was performed by multiplying each column of the normalised decision matrix by its corresponding criterion weight to obtain the weighted normalised decision matrix. The weighted normalised values were calculated using Equation (2.9).

Table 4.9
Decision Matrix with Weights and Normalisation

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
WEIGHT	**0.1670**	**0.1291**	**0.1214**	**0.1525**	**0.2574**	**0.1725**
Abaca	0.0445	0.0622	0.0551	0.0675	0.0346	0.0752
Bamboo	0.1290	0.0349	0.0502	0.0872	0.0555	0.0436
Coir	0.0412	0.0209	0.0155	0.0099	0.2389	0.0577
Jute	0.0334	0.0431	0.0485	0.0761	0.0275	0.0825
Kenaf	0.0534	0.0786	0.0543	0.0675	0.0573	0.0676
Sisal	0.0601	0.0558	0.0604	0.0255	0.0293	0.0866

Step 4: Determination of the positive ideal and negative ideal solutions and degree of closeness

The PIS (A*) and NIS (A^-) were first determined to establish the reference points for evaluating the alternatives. The PIS represented the maximum value of the weighted normalised dataset, while the NIS corresponded to the minimum value. In this example the positive ideal value was identifies as $A^* = 0.1290$, whereas the negative ideal was $A^- = = 0.0334$.

Subsequently, the degree of closeness of each alternative to the ideal solution was calculated using Equation (2.10). This measure quantified the relative proximity of each alternative to the optimal solution by simultaneously considering its distances form both the positive and negative ideal solutions. The complete results of the degree of closeness to the ideal solution were presented in Table 4.10.

Table 4.10
Compared to Negative Ideal Solutions and Positive Ideal Solutions

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
$\mathbf{A^*}$	0.1290	0.0786	0.0604	0.0872	0.2389	0.0866
$\mathbf{A^-}$	0.0334	0.0209	0.0155	0.0099	0.0275	0.0436

Step 5: Determination of separation measures

The separation measures of each alternative form the positive ideal solution (A^*) and the NISs (A^-) were subseqeuntly determined. The measures quantified the

Euclidean distances of each alternative from the ideal and anti-ideal reference point. This separation distance was calculated using Equation (2.11) and (2.12). The complete separation measure for all alternative were presented in Table 4.11.

Table 4.11
Compared to Separation Measure for each Performance Criterion

	Abaca	**Bamboo**	**Coir**	**Jute**	**Kenaf**	**Sisal**
S_i^*	0.2229	0.1936	0.1410	0.2353	0.1987	0.2303
S_i^-	0.0881	0.1316	0.2120	0.0865	0.1001	0.0777

Step 6: Calculation of the relative closeness to the ideal solution

The final step involved determining the relative closeness of each alternative to the ideal solution, which incorporated both the positive ideal solution and the negative ideal solution. The relative closeness coefficient Pi with respect to the ideal solution was calculated using Equation (2.13).

The complete results of the relative closeness for all alternatives were presented in Table 4.12, which formed the basis for the final ranking of alternatives in the TOPSIS analysis.

Table 4.12
Relative Closeness to the Ideal Solution for each Performance

	Abaca	**Bamboo**	**Coir**	**Jute**	**Kenaf**	**Sisal**
Pi	0.2832	0.4047	0.6006	0.2688	0.3351	0.2523

Table 4.12 presented the six natural fibre alternatives ranked according to their relative closeness (Pi) scores. The results indicated that Coir achieved the highest Pi value of 0.6006, signifying its strongest overall performance among the evaluated alternatives. Bamboo ranked second with a Pi score of 0.4047, followed by Kenaf (0.3351), Abaca (0.2832), Jute (0.2688), and Sisal (0.2523).

The superior ranking of Coir suggested that it offered a favourable balance of the evaluated performance criteria, particularly in terms of energy absorption capability and material stability. This finding was consistent with the study reported by Hasan et al., (2021), which highlighted the favourable mechanical behaviour and thermal stability of Coir based composites in structural applications. The comparatively lower rankings of Sisal and Jute indicated reduced overall suitability within the adopted multi criteria evaluation framework, despite their acceptable individual material properties.

Step 7: Establishment of preference ranking

The final preference ranking of the alternatives, based on their respective (Pi) scores, was established and summarised in Table 4.13.

Table 4.13
Overall Ranking of all Alternative Options

Alternatives	Pi	Ranking
Abaca	0.2832	4
Bamboo	0.4047	2
Coir	**0.6006**	**1**
Jute	0.2688	5
Kenaf	0.3351	3
Sisal	0.2523	6

As a result, the ranking outcomes obtained using the integrated CRITIC-TOPSIS method were presented in Table 4.13. The rankings were derived by synthesising data from selected critical performance criteria, resulting in the prioritisation of six natral fibre alternatives. These alternatives were ordered based on their relative closeness to the PIS (Pi) scores. The calculations were implemented using Microsoft Excel 2016 following specified computational procedure. As noted by Guerrero, (2010), spreadsheet tools such as Microsoft Excel has become as commonplace as calculators in the data analysis and DM applications.

As shown in Table 4.13, Coir achieved the highest Pi score of 0.6006, placing it at the top of the ranking. ranked second with a score of 0.4047, followed by Kenaf (0.3351), Abaca (0.2832), Jute (0.2688), and Sisal (0.2523). These results indicated that Coir exhibited the most favourable overall balance of the evaluated performance criteria within the adopted DM framework.

Although the ranking outcomes clearly differentiated the performance of the evaluated alternative, the inclusion of additional criteria could further enhance the comprehensiveness of the natural fibre selection process. In material selection studies, it is essential to consider multiple and context specific variable to support informed and application oriented DM. Consequently, the establishment of well defined selection criteria based on specific functional and design requirements was shown to have a significant influence on the final ranking outcomes.

Based on the obtained results, Coir fibre was identified as a suitabale alternative to conventional materials due to its cost effectiveness, renewability, recyclability,

biodegradability, and environmental friendliness when compared to synthetic fibres. Owing to its versatility, Coir has been widely utilised in various industries, including mat production, yarn manufacturing, rope making, flooring products, insulating panels, packaging materials, and textile goods. Furthermore, Coir has been extensively employed in the automotive and construction sectors to enhance the mechanical performance of polymer composites (Goyat et al. 2022). Consistently, (Onukwuli, Okpala, and Nnaemeka 2022) reported that Coir fibre offers advantages such as low density, a high strength to weight ratio, low cost, and wide availability.

With reference to the results and analysis of the CRITIC-TOPSIS framework development, together with the comparative validation conducted using reliable literature-based datasets, it was concluded that the constructed framework successfully facilated the objective and systematic selection of the optimal natural fibre for the intended application.

4.3 Stage 2: Selected Natural Fibre

This stage presented a decision support framework that utilises the integrated CRITIC-TOPSIS method to select the optimal natural fibre for enhancing bio composites materials in cap toe shoes applications. The proposed framework was developed based in the MCDM approach, in which the CRITIC and TOPSIS methods were applied to analyse case studies involving multiple natural fibre alternative.

The priority weight distribution in the preceding Figure 4.3 was a direct outcome of the CRITIC weighting procedure formulated in Equation (2.2) to (2.6). The Figure 4.3 visually represented the final weights obtained after the systematic application of data normalisation, contrast intensity evaluation, inter criteria correlation analysis, and information content computation. Therefore, the observed dominance the relative magnitude of each criterion was mathematically justified by the CRITIC formulation.

Among the evaluated criteria, elongation at break recorded the highest priority weight (0.1368). This outcome indicated that deformation capability was considered the most critical property for the intended application. In the context of cap toe shoes structures, a higher elongation at break was essential to enable controlled deformation under impact loading, thereby allowing effective energy absorption while reducing the risk of brittle failure. The high weight assigned to this criterion reflected its strong

variability across fibre alternatives and its low correlation with other mechanical properties.

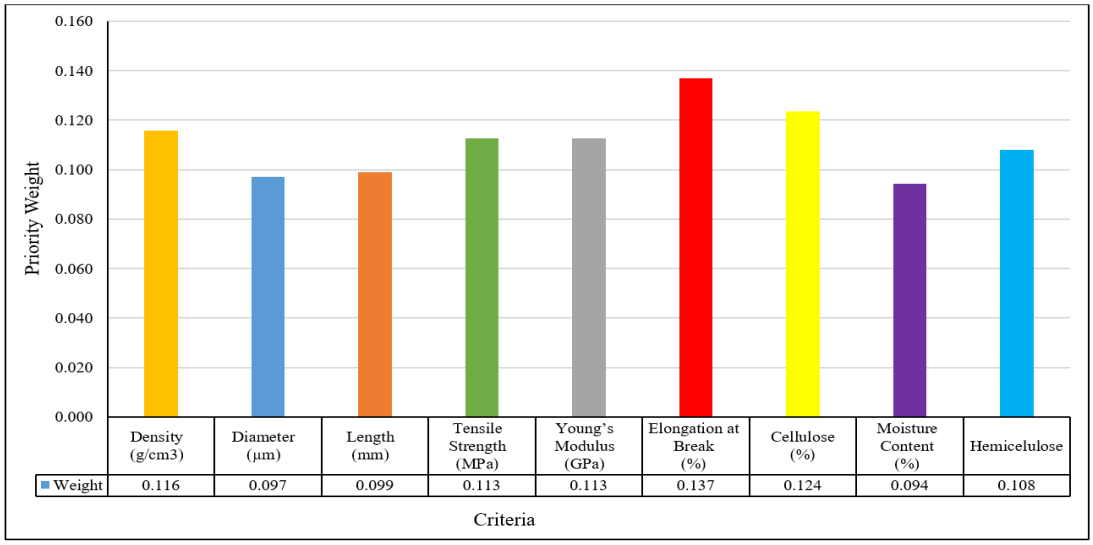


Figure 4.3 Criteria Weight Obtained from CRITIC Method

Cellulose content (0.1237) and density (0.1158) were also assigned relatively high weights. Cellulose content was closely associated with mechanical strength and stiffness of natural fibres, which directly influenced load bearing capacity and structural integrity of composite cap toe shoes. Density, on the other hand, was a key parameter for safety footwear design, as lighter cap toe shoes components contributed to improved wearer comfort without compromising protection. The significant weighting of the criteria highlighted the importance of achieving a balance between strength and lightweight performance.

Tensile strength (0.1126) and Young's modulus (0.1126) exhibited identical priority weights, indicating comparable importance in the DM process. These properties were essential for maintaining the structural stability of the cap toe shoes under strength were required to resist excessive deformation while working synergistically with elongation at break to ensure impact resistance.

Criteria ralated to fibre length (0.0989) and diameter (0.0971) received moderated weights. These geometrical characteristics influenced fibre matrix bonding, load transfer efficiency, and manufacturability of the composite. Although important, their lower weights indicated properties for cap toe shoes performance. The lowest priority weight was assigned to moisture context (0.0942). This result suggested that, within the evaluated dataset, moisture related variability among fibres was less

influential than mechanical and structural criteria. Nevertheless, moisture content remained relevant for durability and long term performance, even though it exerted a smaller impact on the overall ranking.

Overall, the weighting results demonstrated that the CRITIC method prioritised criteria directly associated with impact resistance, deformation behaviour, and structural reliability, which were fundamental requirements for safety cap toe shoes applications. This weighting structure strongly influenced the TOPSIS results and explained why fibres exhibiting balanced performance in high weight criteria, such as elongation at break, stiffness, and density, were favoured in the final ranking.

The TOPSIS analysis was conducted for twelve natural fibres alternative using the criteria weights derived from the CRITIC method. To evaluate the ranking of all alternative, the decision matrix was first established based on the selected performance criteria. The standardised performance ratings were then determined using Equation (2.2). Subsequently, the weighted normalised decision matrix was calculated using Equation (2.6) by incorporating the CRITIC derived weight.

The positive and NIS were then identified using Equation (2.10), followed by the calculation of separation measure using Equation (2.11) and (2.12). Based on these separation distance, the relative closeness to the ideal solution (Pi) was computed using Equation (2.13).

Table 4.14 presents the overall ranking of twelve natural fibre alternative were obtained using integrated CRITIC-TOPSIS method for the selection of suitable reinforcement material for cap toe shoes applications. In this study, the CRITIC method was applied to objectively determine the weights of the evaluation criteria based on their variability and mutual conflict, while the TOPSIS method was employed to rank the fibre alternatives according to their relative closeness to the ideal solution. This combined approach ensured a systematic and unbiased material selection process aligned with the functional demands of protective footwear components.

The results demonstrated that Ijuk fibre achieved the highest ranking with the largest relative closeness value (Pi = 0.5082). This outcome indicated that Ijuk exhibited the most favourable overall performance when evaluated against criteria relevant to cap toe shoes structure, including impact resistance, energy absorption capability, density, stiffness, and structural integrity. The relatively low separation from the PIS (Si^{+} = 0.1291) and the comparatively higher separation from the NIS (Si^{-} = 0.1334) suggested

that Ijuk closely satisfied the desired performance characteristics required for protective cap toe shoes.

Table 4.14
Overall Ranking Selection of Alternative for Natural Fibre

No.	Fibre	Separation measure of the group		Positive ideal	Rank
		Si+	Si-	Pi	
1	**Ijuk**	**0.1291**	**0.1334**	**0.5082**	**1**
2	Ramie	0.1216	0.1229	0.5028	2
3	Coir	0.1577	0.0945	0.3748	3
4	Pineapple	0.1594	0.0796	0.3330	4
5	Flax	0.1556	0.0674	0.3024	5
6	Bamboo	0.1529	0.0520	0.2538	6
7	Hemp	0.1575	0.0488	0.2367	7
8	Banana	0.1627	0.0489	0.2311	8
9	Sisal	0.1670	0.0475	0.2214	9
10	Jute	0.1682	0.0471	0.2189	10
11	Kenaf	0.1618	0.0438	0.2130	11
12	Abaca	0.1664	0.442	0.2100	12

The selection of Ijuk as a potential material was strongly supported by the CRITIC derived weighting structure. Criteria associated with impact loading behaviour and mechanical reliability were assigned higher weight due to their greater contrast intensity and lower correlation with other criteria. These criteria were particularly critical for cap toe shoes, where the component was required to withstand high impact forces while limiting deformation to prevent injury to the wearer. Ijuk's consistent performance across these high weight criteria significantly enhanced its overall closeness to the ideal solution.

In contrast, Ramie fibre which ranked second (Pi = 0.5028), demonstrated comparable mechanical properties but exhibited a slightly less balanced separation profile. Although Ramie showed strong stiffness and strength characteristics, its performance was more sensitive to specific criteria, which reduced its robustness in the multi criteria evaluation. For cap toe shoes application, such sensitivity could increase the risk of excessive deformation or inconsistent energy absorption under impact conditions.

From a practical engineering perspective, the prioritisation of Ijuk was considered appropriate for cap toe shoes design, where a balance between impact resistance, lightweight construction, and manufacturability was essential. Natural fibre reinforced polymer was required to absorb and dissipate impact energy efficiently while maintaining structural stability and user comfort. Ijuk's favourable balance between stiffness and toughness contributed to reduced stress concentration and controlled deformation, which were critical for compliance with safety footwear performance requirements.

Furthermore, the use of Ijuk aligned with sustainability and cost considerations increasingly emphasised in safety footwear manufacturing. Its local availability, renewability, and compatibility with polymer matrix supported its selection as a variable alternative to conventional synthetic reinforcements.

Overall, the integrated MCDM results provided strong and consistent justification for selecting Ijuk fibre as a potential reinforcement material for cap toe shoes. The outcome supported its progression to subsequent numerical impact simulations and experimental validation, thereby reinforcing the relevance and applicability of Ijuk fibre in the development of sustainable and high performance safety footwear components.

4.3.1 CRITIC-TOPSIS Evaluation Results

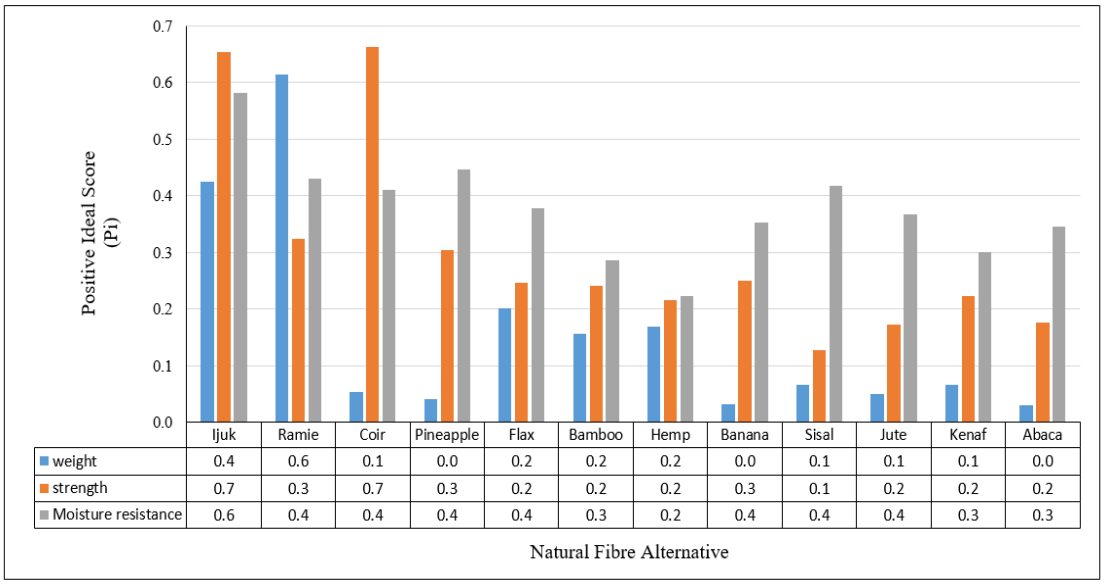
Table 4.14 (column 6) presents the final ranking derived from the CRITIC-TOPSIS method. By synthesising the critical criteria data, twelve natural fibres were evaluated and ordered according to their Positive Ideal Solution (Pi) scores. These calculations were performed using Microsoft Excel 2016, reflecting Guerrero et al. (2010) observation regarding the ubiquity and reliability of spreadsheet tools in modern data analysis. The three primary factors assessed were weight, strength, and moisture resistance. The sub-criteria of the "strength" criterion included tensile strength, Young's modulus, and elongation at break. The previously mentioned sub-criteria focused only in the perspective of mechanical qualities, as the cap toe shoes design required strong materials for optimal performance.

It was crucial to recognise that every natural fibre possessed unique properties that affect its suitability for specific industrial applications in terms of mechanical behaviour and performance (Peças et al. 2018). Figure 4.4 illustrated the positive ideal

scores of the selected natural fibre alternatives with respect to the three dominant criteria, namely “weight”, “strength”, and “moisture resistance”. These criteria were previously identified as critical for safety shoe cap toe shoes applications based on the CRITIC-TOPSIS results. The graphical comparison provided a clear visual assessment of how each fibre performed relative to the ideal solution under each major criterion.

With respect to the “Weight” criterion, Ramie recorded the highest positive ideal score, followed by Ijuk. This result indicated that Ramie and Ijuk offered superior lightweight characteristics compared to the other fibres, which was an important consideration for safety footwear design where wearer comfort and reduced fatigue were required. Fibres such as Abaca, Banana, and Pineapple exhibited comparatively low weight scores, suggesting less favourable performance in terms of mass efficiency for cap toe shoes components.

In term of “Strength”, Coir and Ijuk demonstrated the highest positive ideal scores, with values exceeding those of all other alternatives. This outcome suggested that both fibres possessed strong load bearing capability, which was essential for resisting impact forces experienced by cap toe shoes structures during service conditions. Ijuk’s strength score was comparable to that of Coir, indicating its suitability for applications requiring high mechanical resistance.



	Ijuk	Ramie	Coir	Pineapple	Flax	Bamboo	Hemp	Banana	Sisal	Jute	Kenaf	Abaca
weight	0.4	0.6	0.1	0.0	0.2	0.2	0.2	0.0	0.1	0.1	0.1	0.0
strength	0.7	0.3	0.7	0.3	0.2	0.2	0.2	0.3	0.1	0.2	0.2	0.2
Moisture resistance	0.6	0.4	0.4	0.4	0.4	0.3	0.2	0.4	0.4	0.4	0.3	0.3

Figure 4.4 Natural Fibre Score with Corresponding Main Criteria

Regarding “moisture resistance”, Ijuk achieved the highest positive ideal score, followed by Pineapple and Ramie fibres. This result was particularly significant for

safety shoes, as cap toe shoes components were often exposed to humid and wet working environments. Higher “moisture resistance” contributed to improved durability, dimensional stability, and retention of mechanical properties over time. Fibres with lower “moisture resistance” scores, such as Bamboo and Hemp, were therefore considered less favourable for long term footwear applications.

When the three criteria were considered collectively, Ijuk emerged as the most balanced alternative. Although Ramie excelled in weight and Coir performed strongly in strength, neither fibre demonstrated consistently high performance across all three criteria. In contrast, Ijuk achieved high positive ideal scores in “Weight”, “Strength”, and “moisture resistance” resistance simultaneously, indicating its robust multi criteria performance. This balanced behaviour was critical in cap toe shoes applications, where trade offs among mechanical protection, comfort, and environmental durability were undesirable.

Overall, Figure 4.4 supports the CRITIC-TOPSIS ranking results by visually confirming why Ijuk was selected as potential natural fibre for cap toe shoes. The graph demonstrated that Ijuk’s superior performance was not driven by a single dominant criterion by rather by its consistent proximity to the ideal solution across all major requirements. Consequently, the figure reinforced the justification for selecting Ijuk as a potential reinforcement material for cap toe shoes structures and validated the effectiveness of the adopted MCDM framework.

Figure 4.5 illustrates the final synthesis of ranking results obtained form the CRITIC-TOPSIS method by comparing the relative ranks of natural fibre alternatives with respect to weight, strength, and moisture resistance. This figure integrated the individual criterion based ranking into a consolidated visual representation, thereby demonstrating how each alternative performed across the dominant criteria identified in the weighting analysis.

The ranking trends indicated noticeable variation in fibre performance depending on the evaluated criterion. Several fibres exhibited string performance in one criterion but were penalised by lower rankings in others, highlighting the trade offs inherent in natural fibre selection. For the example, fibre such as Bamboo and Banana recorder moderate to good rankings in weight but displayed weaker performance in strength or moisture resistance, which reduced their overall suitability for protective footwear applications.

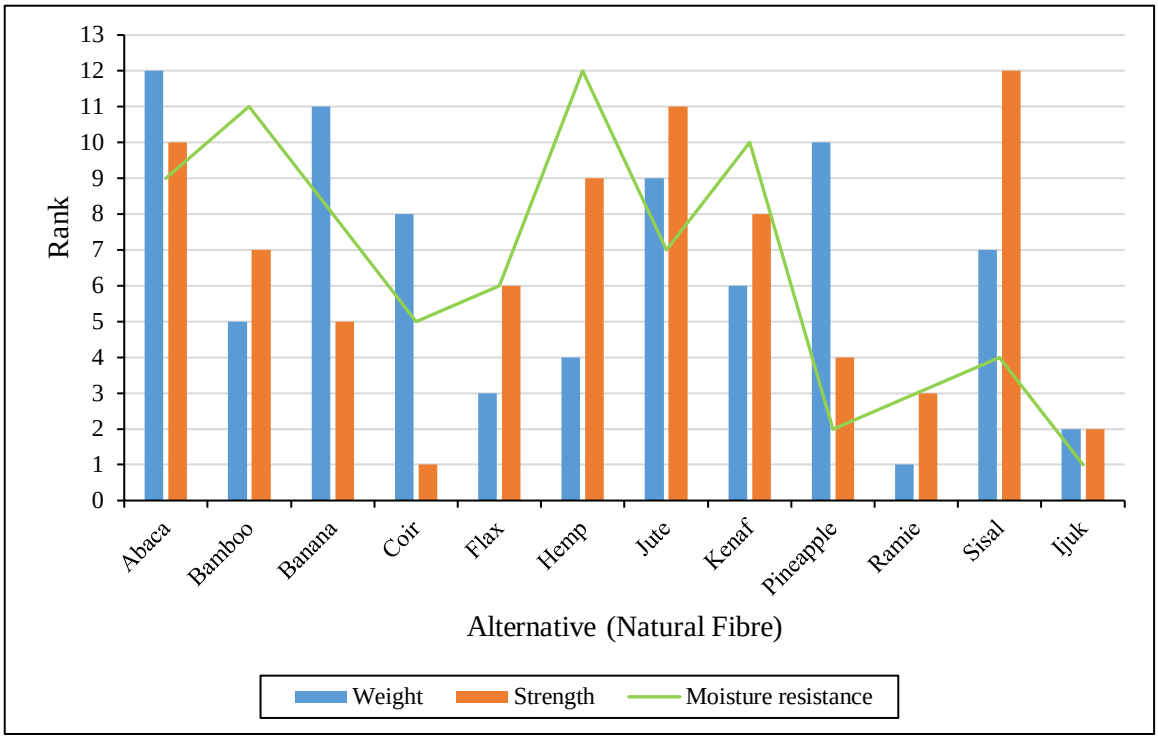


Figure 4.5 The Final Synthesis Results of the CRITIC-TOPSIS Method are Presented for all Criteria

With respect to the "Weight" criterion, Ramie and Ijuk achieved superior rankings, indicating their advantages in lightweight, performance, which was essential for reducing wearer fatigue in safety shoes. In contrast, fibres such as Abaca and Pinedapple were ranked lower in weight, suggesting less favourable mass efficiency for cap toe shoes sturctures. In terms of "Strength", Coir and Ijuk demonstrated strong rankings, reflecting their ability to withstand mechanical loads and impact forces encountered by cap toe shoes. Fibres with lower strength rankings were considered less reliable for providing adequate toe protection under high impact conditions.

The "moisture resistance" rankings further differentiated the fibre alternatives, Ijuk consistently ranked among the top perfomer's, indicating superior resistance to moisture related degradation. This characteristic was particularly important for safety shoe applications, as exposure to wet and humid environments could adversely affect material durability and mechanical performance. Fibres such as Hemp and Bamboo exhibited lower moisture resistance rankings, which limited their suitability for long term footwear use.

When all criteria were synthesised, Ijuk fibre emerged as the most consistently high ranked alternative across "weight", "strength", and "moisture resistance". Unlike

other fibres that showed strong performance in isolated criteria, Ijuk maintained favourable rankings across all three dominant attributes, thereby minimising performance trade offs. This balanced ranking profile justified its selection as the optimal natural fibre cap toe shoes applications.

Overall, Figure 4.5 confirms the effectiveness of the CRITIC-TOPSIS synthesis in integrating multiple performance dimensions into a single evaluative framework. The results demonstrated that the final material selection was governed by holistic performance rather that isolated excellence. Consequently, the consistent high ranking performance of Ijuk reinforced its suitability for further numerical simulation as a reinforcement material in cap toe shoes structures.

Figure 4.6 presents a detailed comparison of the ranking outcomes for the evaluated natural fibre alternatives under three key criteria; (a) moisture resistance, (b) strength, and (c) weight. These criteria were selected due to their critical relevance in engineering applications involving NFRC, particularly for safety related components where durability, mechanical integrity, and ergonomic performance must be simultaneously satisfied. The rankings were interpreted such that a lower numerical rank corresponded to superior performance for the respective criterion.

As illustrated in Figure 4.6 (a), the ranking for moisture resistance exhibited considerable dispersion across the alternatives, indicating substantial differences in hygroscopic behaviour among the natural fibres. Fibres such as Ijuk and Banana achieved relatively better rankings, suggesting superior resistance to moisture ingress. This performance can be attributed to their higher lignin content and more compact fibre morphology, which reduced the availability of hydrophilic sites for water absorption. Conversely, fibres such as Sisal and Jute were ranked less favourably, reflecting their higher cellulose content and more open microstructure, both if which promoted moisture uptake. This observation is particularly significant, as excessive moisture absorption is known to adversely affect fibre matrix interfacial bonding, accelerate material degradation, and compromise long term mechanical performance.

The ranking trends for strength, illustrated in Figure 4.6 (b), revealed a different performance pattern. Kenaf and Hemp achieved superior rankings, indicatin enhanced mechanical strength relative to the other alternatives. This result was consistent with their reported high tensile strength, favourable microfibril orientation, and relatively uniform fibre geometry, which collectively facilitated efficient stress transfer in composite systems. Conversely, fibres such as Coir and Jute were associated with lower

rankings, reflecting comparatively lower strength performance under this criterion. Although Coir is often recognised for its toughness capability, its lower tensile strength limited its ranking in strength dominated evaluations.

The ranking outcomes for weight, presented in Figure 4.6 (c), further highlighted the trade off inherent in natural fibre selection. Lightweight fibres such as banana and Bamboo were ranked more favourably. In contrast fibres such as Coir and Sisal exhibited lower rankings due to their density, which increased the overall composite mass. Weight was a particularly critical criterion for ergonomically sensitive applications, where reduced mass directly influenced user comfort and fatigue.

Overall, Figure 4.6 demonstrates that no single natural fibre alternative consistently outperformed the others all evaluated criteria. Each fibre exhibited distinct advantages and limitations depending on the specific performance requirement. These findings highlight the necessity of adopting a luti criteria DM approrah to balance competing criteria and to support a rational and defensible material selection process.

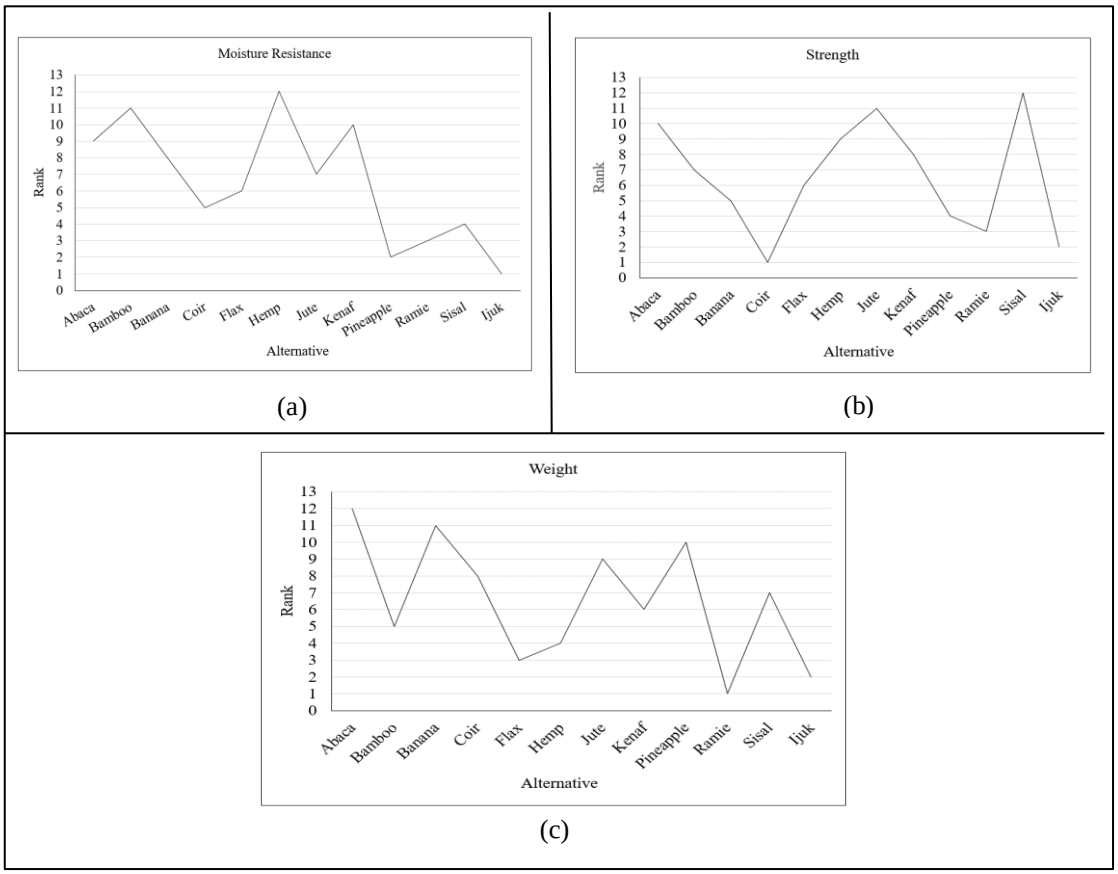


Figure 4.6 (a) Alternatives Result for the Moisture Resistance, (b) Alternatives Result for the Weight, (c) Alternatives Result for the Strength

Although the results were extensively validated, the authors suggested that the natural fibre selection approach could have been more comprehensive by incorporating additional features from other criteria. When making decisions, it was essential to consider multiple aspects in formulating the necessary criteria. Consequently, while selecting natural fibres, decision makers must establish highly accurate selection criteria based on specific requirements, as these would impact the final selection outcomes.

Further measurements were recommended to determine the timing of the fibre harvest, extraction techniques, aspect ratio, and the pre-treatment and storage strategies of the fibre (Khoo et al. 2023; Wu et al. 2020). Several factors, such as the adhesion between the fibre and matrix, the fibre volume fraction, the fibre aspect ratio (l/d), and the fibre orientation, affected the mechanical characteristics of reinforcement in polymer composites (Stojčić et al. 2019). Furthermore, the choice of surface treatment and the application of nanotechnology could significantly impact the final selection results by enhancing the interfacial bonding with biopolymer matrices (Saba et al. 2017). The absence of data on the properties of natural fibres and related information in established commercial databases posed a significant obstacle in the selection process. Sapuan et al., (2011) emphasised the necessity of establishing a comprehensive dataset of natural fibre substitutes and underscored the importance of reliable and transparent data sources on natural fibre characteristics to support informed and objective DM.

4.3.2 Results for Sensitivity Analysis

The last process of implementing CRITIC-TOPSIS is the sensitivity analysis. Table 4.15 summarised the sensitivity analysis conducted to examine the robustness of the CRITIC-TOPSIS ranking results under variations in criteria weights. The analysis evaluated the stability of the ranking by applying incremental changes to the weights of the dominant criteria, namely “strength”, “weight”, and “moisture resistance”. This approach was employed to assess whether the original ranking outcome was sensitive to reasonable perturbations in the weighting structure.

The results indicated that Ijuk fibre consistently maintained the top ranking in most scenarios, particularly under 20% increment of “strength”, the 20% increment of “moisture resistance”, and combine 10% increment of “moisture resistance” and “strength”. This consistency demonstrated that the selection of Ijuk as the optimal material was not highly sensitive to moderate changes in the importance assigned to

individual criteria. For, a DM perspective, this stability suggested a high degree of confidence in the robustness of the proposed material selection framework. Cap toe shoes require lightweight components to ensure that the safety shoes remain lightweight. However, cap toe shoes must possess strength, as stated in the report by Kropidłowska et al. (2020). Strength and moisture resistance are key qualities of the materials used in cap toe shoes to ensure that the shoes can protect the feet from falling objects (Iacopo Bianchi et al. 2022) and wetting due to environmental moisture (Kuklane 1997).

Table 4.15
Summary of Sensitivity Analysis

Rank	Original result	20% increment of Strength	20% increment of Weight	20% increment of Moisture Resistance	10% increment of Weight and Strength	10% increment of Moisture Resistance and Strength
#1	**Ijuk**	**Ijuk**	Ramie	**Ijuk**	Ramie	**Ijuk**
#2	Ramie	Ramie	**Ijuk**	Ramie	**Ijuk**	Ramie
#3	Coir	Coir	Coir	Coir	Coir	Coir
#4	Pineapple	Pineapple	Pineapple	Pineapple	Pineapple	Pineapple
#5	Flax	Flax	Flax	Flax	Flax	Flax
#6	Bamboo	Bamboo	Bamboo	Bamboo	Bamboo	Bamboo
#7	Hemp	Hemp	Hemp	Sisal	Hemp	Hemp
#8	Banana	Banana	Banana	Banana	Banana	Banana
#9	Sisal	Jute	Sisal	Hemp	Jute	Sisal
#10	Jute	Kenaf	Jute	Jute	Sisal	Jute
#11	Kenaf	Sisal	Kenaf	Abaca	Kenaf	Kenaf
#12	Abaca	Abaca	Abaca	Kenaf	Abaca	Abaca

In contrast, a rank interchange between Ijuk and Ramie was observed when 20% increment in the weight criterion and combined 10% increment of weight and strength were applied. Under these scenarios, Ramie temporarily occupied the first rank while Ijuk shifted to the second position. This behaviour indicated that Ramie exhibited superior performance specifically under conditions where lightweight performance was strongly emphasised. However, the overall ranking pattern showed that this interchange

was limited to scenarios dominated by weight considerations and did not persist across the majority of tested cases.

The middle-ranked alternatives, including Coir, Pineapple, Flax, and Bamboo, demonstrated high ranking stability across all sensitivity scenarios. Their positions remained unchanged or exhibit minimal variation, suggesting that their performance profiles were relatively insensitive to moderate changes in criteria weights, this stability reflected their consistent, albeit moderate, performance across the evaluated criteria.

Greater ranking variability was observed among the lower ranked alternatives, particularly Jute, Sisal, Kenaf, and Abaca. These fibres experienced noticeable rank shifts when criteria weights were perturbed, indicating that their overall performance was more sensitive to weighting changes. Such sensitivity implied weaker multi criteria robustness, thereby limiting their suitability for cap toe shoes applications where reliable and balanced performance was required.

From an application orient perspective, the sensitivity analysis reinforced the suitability of Ijuk fibre for cap toe shoes structure. The ability of Ijuk to retain a top ranking across multiple weighting scenarios demonstrated its strong and balanced performance in “strength”, “moisture resistance”, and acceptable “weight” characteristics. This robustness was critical for safety footwear design, where variation in design priorities or operational conditions should not compromise material selection decisions.

The ranking results obtained from the TOPSIS analysis are represented by the relative closeness coefficient (Pi), which quantifies the distance of each material from the ideal and negative ideal solutions. A higher Pi value indicates that the material exhibits better overall performance across all evaluated criteria and is therefore closer to the optimal solution. In this study, Ijuk achieved the highest Pi value, indicating its superior balance of mechanical strength, low density, and moisture resistance compared to other alternatives.

The ranking can be interpreted as a reflection of the material’s ability to satisfy the conflicting requirements of cap toe shoes. For instance, although certain fibres such as Ramie demonstrate competitive strength properties, their comparatively higher density or moisture sensitivity reduces their overall ranking. Conversely, Ijuk maintains a balanced performance across all criteria, which is critical in application where no single property can dominate the selection process.

Additionally, the consistency of Ijuk's ranking across sensitivity analysis scenarios further reinforces its robustness as the optimal material choice as illustrated in Table 4.15. This indicates that the selection outcome is stable even when variations in criteria weight are introduced, thereby increasing confidence in the reliability of the DM framework.

4.4 Stage 3: Selected Polymer Matrix for Cap Toe Shoes

PMC consist of a matrix made from either thermosetting polymers or thermoplastics, reinforced with dispersed fibres such as carbon, glass, Kevlar, or metal (Dang et al. 2012; Krishan K. Chawla 2019; Park and Seo 2011; Sayam et al. 2022). Due to their ease of fabrication and cost effectiveness, PMC are widely utilised in engineering. The polymer matrix, formed through organic polymerisation, is favoured for its wear and corrosion resistance, as well as its exceptional strength to weight ration properties that are particularly critical for safety footwear, such as cap toe shoes.

The study utilised the PDCA cycle, a continuous improvement model that ensures flexibility and detailed planning in complex processes (Arredondo-Soto et al. 2021). While previous study explored MCDM, the specific integration of CRITIC-TOPSIS within a PDCA framework for PMC selection had not been adequately explored.

To bridge this research this gap, this study implemented an integrated CRITIC-TOPSIS-PDCA methodology. The CRITIC method was utilised to determine objective weights, thereby eliminating the need for subjective pairwise attribute comparisons. Subsequently, TOPSIS was applied to identify the optimal PMC candidates. This integration minimised the potential for bias inherent in human DM and provided a robust protocol for designers and material engineers.

4.4.1 Phase 1: Plan

The "Plan" phase focused on defining the decision objectives and establishing systematic procedures to support the material selection process. In alignment with the PDCA methodology, Ishikawa diagrams were utilised to identify, categorise, and structure the key factors influencing composite material performance and sustainability criteria. This structured analysis provided a foundational input for the subsequent

CRITIC-TOPSIS evaluation, as illustrated in Figure 4.7. Figure 4.7 presents a focused Ishikawa diagram, also referred to as Cause-and-Effect Diagram, which systematically for engineering applications. This analytical framework serves as a structured visualisation tool to trace, categorise, and rationalise the underlying causes that collectively determine the suitability of a polymer for NFRC structures. Drawing upon principles of design for performance and manufacturability, the diagram organises these factors into three major categories; Weight, Environment, and Performance, which together encompass the essential engineering domains governing material behaviour and selection outcomes.

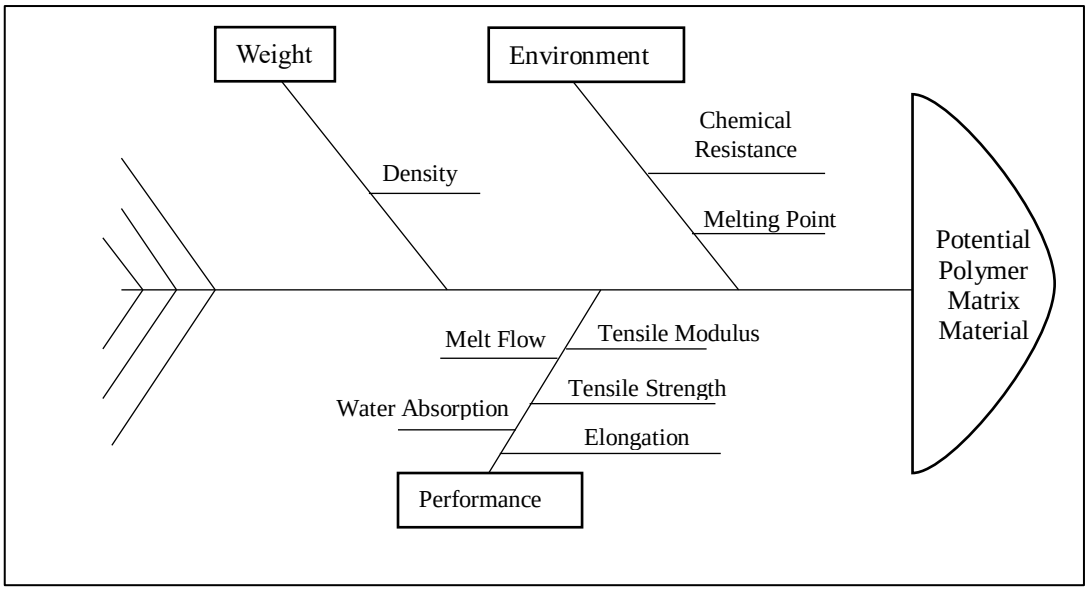


Figure 4.7 Ishikawa Diagram of Selection Criteria for Polymer Matrix

Under the Weight category, Density is identified as the dominant parameter, as it directly correlates with the overall mass of the component and consequently influences energy efficient, ergonomics, and load bearing optimisation. In lightweight engineering design, such as protective footwear components or structural composites, density reduction without compromising mechanical integrity remains a key design challenge.

The Environment category addresses the material interaction with its operational and service conditions. Two attributes, chemical resistance and Melting Point, are highlighted as critical contributors. Chemical Resistance ensures that the material retains its physical and mechanical integrity when exposed to aggressive agents such as moisture, solvents, or industrial chemicals, which is vital for durability and long

term reliability (Qi, Tian, and Xian 2023). Meanwhile, the Melting Point defines the material thermal stability and dictates its maximum service heat loads and manufacturing conditions. These environmental considerations collectively ensure that the selected material can withstand harsh operating environments without degradation or loss of functionality (Ahmed et al. 2024).

The performance category constitutes the most comprehensive dimension of the diagram, encompassing both mechanical properties and processing characteristics that define the material functional capability. Water Absorption is a critical environmental mechanical linkage property that affects dimensional stability, surface quality, and long term mechanical strength, particularly in humid or aqueous environments (Deng et al. 2010).

By methodically structuring these interrelated parameters, the Ishikawa diagram not only clarifies the complex network of influencing factors but also provides a conceptual framework for rational material selection. This systematic approach reflects the principle design optimisation and engineering DM, enabling researchers and engineers to prioritise key material attributes based on performance critical requirements, environmental adaptability, and manufacturability hallmarks of an effective, evidence driven material design methodology.

4.4.2 Phase 2: Do

Figure 4.8 illustrates the four hierarchical levels of the decision structure implemented during the “Do” phase. The descending order of these levels reflected the deviation of the ranking criteria from Table 4.16 and Figure 4.6. At the highest level of the hierarchy, the goal defined the principal objective of the analysis, namely the identification of the most suitable polymer matrix material capable of satisfying the functional, structural, and environmental requirements of a protective cap toe shoes. This overarching objective guided the DM process and ensured consistency between the selected material properties and the intended end use performance.

The second level of the hierarchy introduces three overarching criteria; Performance, Weight, and Environment. It collectively encapsulates the essential design and operational considerations. These criteria represent the critical engineering dimensions governing material suitability. Performance focuses on the mechanical and processing capabilities of the polymer. Weight emphasises material density and its

direct impact on comfort and energy efficiency, and Environment assesses durability and stability under varying thermal and chemical conditions. Together, these criteria form a balanced evaluation triad, integrating strength, functionality, and sustainability within a single decision structure.

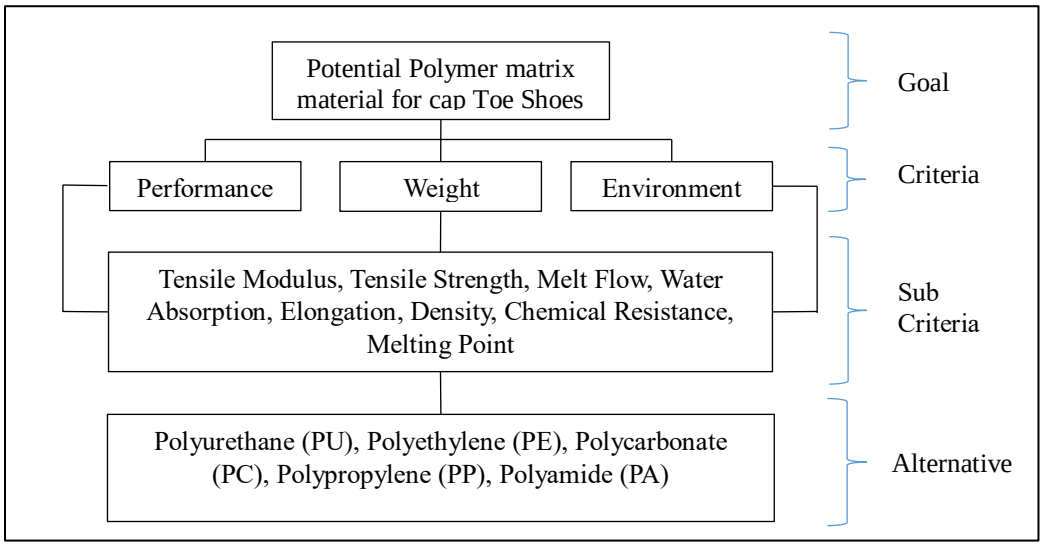


Figure 4.8 The Structural Hierarchy for the Selection of the Materials of Polymer Matrix Material for Cap Toe Shoes

At the third level, each criterion is further decomposed into quantifiable sub-criteria, representing the measurable parameters that directly influence the material behaviour and manufacturability. These include Tensile Modulus, Tensile Strength, and elongation at break, which define the mechanical robustness, stiffness, and ductility of the polymer matrix attributes crucial for impact absorption and load bearing performance is safety footwear applications. Melt Flow Index (MFI) characterises process ability and determines the ease of moulding and shaping during production, ensuring manufacturing consistency. Density serves as a key indicator of lightweight potential, directly influencing the ergonomic comfort of the end product. Meanwhile, Water Absorption, chemical resistance, and Melting Point evaluate environmental resilience, addressing factors such as moisture uptake, resistance to chemical degradation, and thermal endurance. All vital for ensuring long term reliability in diverse working conditions.

At the base of the hierarchy reside the alternatives, compromising five potential polymer candidates; Polyurethane (PU), Polyethylene (PE), Polycarbonate (PC), Polypropylene (PP), and Polyamide (PA). These alternatives were selected based on

their widespread industrial relevance, availability, and proven applicability in polymer composite and footwear manufacturing. Each material possesses unique strengths and limitations, making systematic comparison and ranking through the MCDM process both necessary and valuable.

This hierarchical decomposition not only clarifies the logical relationships among the goal, criteria, and sub-criteria but also enhances the transparency and consistency of the DM process. By structuring the problem in this manner, the final material selection is grounded in objective evaluation rather than subjective judgement. The integration of this hierarchy within an MCDM framework, its supported by weighting techniques such as CRITIC and ranking methods like TOPSIS to ensure that the resulting decision is robust, data driven, and aligned with the specific design, performance, and sustainability requirements of the cap toe shoes application.

Table 4.16 presents a summary of the established selection criteria. The research was divided into three subgroups to implement the CRITIC-TOPSIS methodology, utilising the Microsoft Excel application for calculations.

Table 4.16
Summary of Decision Criteria in Structural Hierarchy

Decision Criteria	**Description**
Weight	In the design of cap toe shoes, the establishment of weight standards necessitates a critical evaluation of material dimensions and density. These physical attributes are fundamental to the engineering process, as they directly influence the feasibility of creating lightweight components that do not compromise that do not compromise on essential performance criteria.
Environment	The material selection criteria encompassed recyclability, biodegradability, and operational safety, specifically prioritising low emissions during both fabrication and service life.
Performance	The optimal performance of cap toe shoes is defined by their capacity to dissipate maximal kinetic energy during impact events. This mechanism relies on the toe cap's ability to absorb energy through controlled axial collapse prior to the structural failure of adjacent components. In this context, thoughnes is characterised as the material's ability to absorb energy prior to fracture, necessiting high tensile strength and environmental durability. Consequently, utilising materials with superior mechanical properties directly correlates to enhanced occupational safety and toe protection for workers.

Source: Mastura et al., 2017; Yusof et al., 2018

Manufacturers aimed to enhance the durability of cap toe shoes while simultaneously reducing weight and maintaining high performance. Toughness was identified as a critical performance attribute in safety footwear, as higher toughness improved energy absorption capability, thereby enhancing worker safety and comfort (I. Bianchi et al. 2022). To achieve optimal toughness, the selected material was required to withstand mechanical deformation per unit volume prior to failure, demonstrating and enhanced ability to absorb kinetic energy loading.

The product design specification (PDS), presented in Table 4.17, outline the key criteria for material selection in identifying the most suitable polymer matrix for cap toe shoes (Kurre 2018). Among these criteria, chemical resistance was recognised as a vital property, referring to a material's ability to resist degradation or damage when exposed to corrosive substances such as acids, bases, or oxidising agents. This property was particularly critical for applications in chemically hazardous environments and played a significant role in both material selection and overall design effectiveness (William D. Callister and David G. Rethwisch; 2014).

Table 4.17
Summary of the Product Design Specification for the Selection of Polymer Matrix

Properties	**Characteristic / value**
Tensile Modulus	High
Tensile Strength (durability)	High
Melt Flow	Low
Water Absorption	High
Elongation (toughness)	High
Density	Low
Chemical Resistance	High
Melting Point	High

The influence of chemical resistance on material selection involved factors such as material type and properties, environmental exposure conditions, cost, and availability (Ashby;, Shercliff, and Cebon; 2014). Conversely, its impact on design performance encompasses durability and lifespan, structural integrity, as well as weight and efficiency (Shackelford 2015). In Summary, chemical resistance was a key factor determinant affecting the durability, safety, and functional performance of the cap toe shoes design. Accordingly, appropriate material selection and strategic design

considerations were essential to achieving optimal functionality, particularly in chemically aggressive operating environments (Mahmoud 2020).

Additionally, the selected material was expected to achieve a high elongation value, reflecting superior toughness. Further requirements comprised reliable availability without resource constraints, low moisture content to minimise fibre cracking, and strong tensile performance to ensure durability in long term service.

4.4.3 Phase 3: Check

In the Check phase of the PDCA cycle, the polymer matrix material properties presented in Table 4.18 were systematically evaluated to assess their suitability against the predefined performance, weight, and environmental criteria required for biodegradable composite development. This phase focused on verifying whether the selected polymer matrix fulfilled the functional and sustainability requirements established during the Plan stage.

The mechanical performance indicators, particularly Tensile Modulus and tensile strength, revealed clear distinctions among the polymer matrix, PC and PA exhibited superior stiffness and strength, indicating excellent load bearing capability. However, their relatively high melting points and densities may pose challenges in terms of processability and weight optimisation. In contrast, PU an PE demonstrated lower tensile properties but offered significantly higher elongation at break, reflecting enhanced ductility and impact energy absorption potential, which are desirable characteristics for protective footwear applications.

Overall, the Check phase analysis confirmed that while high performance polymers such as PC and PA excel in mechanical strength, lightweight and moisture resistant polymers such as PP and PE offer a more balanced performance profile. These findings validate the necessity of multicriteria evaluation prior to material selection and provide a robust basis for DM in the subsequent Act phase of the PDCA cycle, where optimisation and final material selection are undertaken.

Table 4.18
Polymer Matrix Material Properties

Polymer Matrix	Performance					Weight	Environment	
	Young Modulus (GPa)	Tensile Strength (MPa)	Melt Flow (G/10 Mm)	Water Absorption (@24h) (%)	Elongation	Density (g Cm^-3)	Chemical Resistance	Melting Point (°C)
Polyurethane (PU)	0.028 to 0.72	5 to 28	4 to 49	0.15 to 0.19	60 to 550	1.15 to 1.25	0.4	220 to 230
Polyethylene (PE)	0.15	10 to 18	0.25 to 2.6	0.015 to 0.2	442 to 543	0.918 to 0.919	0.76	104 to 113
Polycarbonate (PC)	2.2	65.5	3 to 80	0.12	60	1.2	-	288 to 316
Polypropylene (PP)	1.5 to 1.75	28 to 39	0.47 to 350	0.01 to 0.02	43 to 73.2	0.89 to 0.91	0.76	134 to 165
Polyamide (PA)	0.7 to 3.3	40 to 86	15 to 75	0.3	50	1.03 to 1.16	-	211 to 265

Source: Mastura et al. 2018; Vaidya and Chawla 2008

4.4.4 Phase 4: Act

Building upon the findings validated in the Check phase, Figure 4.9 presented the MATLAB workspace used in the Act phase for the implementation of the integrated CRITIC-TOPSIS DM framework. In the preceding *Check* phase, the suitability of polymer matrix materials was evaluated against predefined performance, weight, and environmental criteria, and the reliability of the selected parameters was verified. These verified inputs were subsequently utilised in the *Act* phase to operationalise the final optimisation and ranking process.

As illustrated in Figure 4.9, the CRITIC method was first applied to objectively derive criterion weights based on contrast intensity and inter criteria correlation, thereby reducing subjectivity in the weighting process. The resulting CRITIC weights, which were displayed in the MATLAB command window and workspace, were then directly incorporated into the TOPSIS procedure to compute the relative closeness of each alternative to the idela solution. This integration ensured that the final material ranking was grounded in the validated evaluation outcomes established during the *Check* phase.

The MATLAB workspace further facilitated transparency, repeatability, and rapid iteration, allowing adjustments to be made efficiently where necessary. Consequently, the *Act* phase effectively translated the verified analytical outcomes from

the *Check* phase into an implementable and optimised material selection decision, thereby closing the PDCA loop.

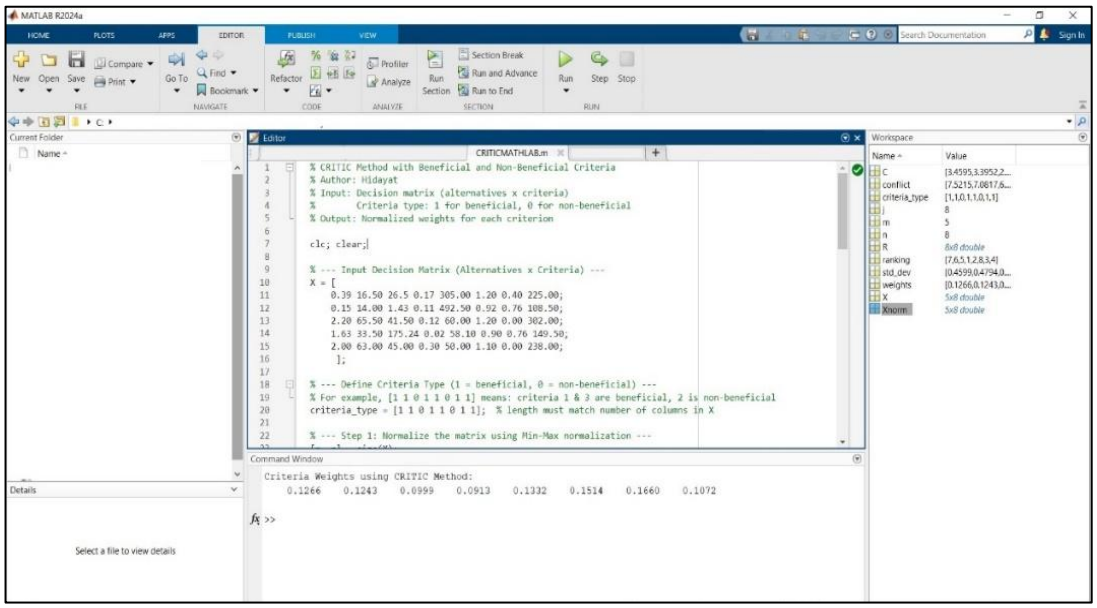


Figure 4.9 MATLAB Workspace for the Implementation of the Integrated CRITIC-TOPSIS Method

4.4.4.1 Results of the CRITIC Method using MATLAB

The CRITIC method objectively determines the relative importance of each criterion based on both its contrast intensity (standard deviation) and its level of conflict or correlation with other criteria. In this study, eight material properties were evaluated to determine their influence on polymer matrix selection for cap toe shoes application. The weights from the CRITIC method analysis as shown in Table 4.19, reveal distinct differences in the contribution of each criterion.

The results indicate that chemical resistance obtained the highest weight (0.1664), signifying that it contributes most significantly to the overall decision process. This outcome suggests that variation among materials with respect to chemical resistance is high, and this criterion exhibits relatively low correlation with the others. Therefore, it provides substantial and unique information in differentiating material performance. A logical finding considering that chemical degradation is a critical factor affecting the long term durability of cap toe shoes materials exposes to perspiration, moisture, or workplace chemicals.

The second most influential criterion, Density (0.1515), reflects its importance in determining the overall weight and comfort of the footwear. In safety shoes applications, a lower density material contributes to lighter footwear, improving user ergonomics and comfort without compromising strength. The third ranked criterion, elongation at break (0.1334), also plays a vital role in impact absorption and flexibility. Both essential for ensuring that the cap toe shoes and deform safely under compression or impact without catastrophic failure.

Conversely, Water absorption (0.0911) and MFI (0.00998) were assigned the lowest weights, implying that these properties, although relevant, exhibit lower variability among the alternative materials or share string correlations with other criteria. For instance, a materials water absorption behaviour often correlates with its chemical resistance and density, thus reducing its independent informational contribution to the overall decision matrix.

Table 4.19
Result of CRITIC Weight Calculation using Microsoft Excel

Properties	Weight	Rank
Tensile Modulus (GPa) / C1	0.1266	4
Tensile Strength (MPa) / C2	0.1242	5
Melt Flow (g/10 mm) / C3	0.0998	7
Water Absorption (@24h) (%) / C4	0.0911	8
Elongation at Break / C5	0.1334	3
Density / C6	0.1515	2
Chemical Resistance / C7	0.1664	1
Melting Point (◦C) / C8	0.1071	6

Interestingly, Tensile Modulus (0.1266) and Tensile strength (0.1242) occupy mid-range positions in the ranking. Although mechanical strength is undeniably important, their moderate weights suggest that variations among candidate materials in this aspect are not as significant as in other properties, or that these two mechanical properties are highly correlated with one another, which aligns with the theoretical basis of the CRITIC method. The moderate correlation between strength related parameters reduced their individual weighting impact.

When comparing the CRITIC method calculation result obtained from Microsoft Excel shown in Table 4.19, and MATLAB shown in Figure 4.10, both methods produced identical weight values and rankings for all criteria. This consistency

confirms the accuracy and validity of the MATLAB program developed in this study. The identical outputs also indicate that the mathematical operations, particularly normalisation, correlation computation, and weight determination, were correctly implemented in the MATLAB script. Furthermore, this alignment demonstrates that MATLAB can serve as a reliable and automated tool for conducting MCDM analyses, eliminating potential manual errors that might occur during spreadsheet calculations.

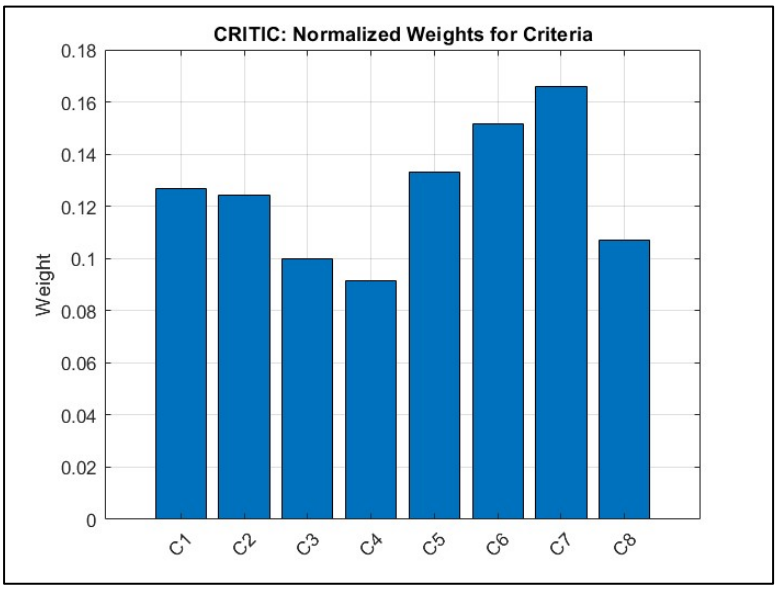


Figure 4.10 CRITIC Weight Rank in MATLAB

Overall, the obtained CRITIC method weights demonstrate that chemical durability and material density are the most critical parameters for material selection in this context. This implies that the optimal cap toe shoes material should primarily exhibit string resistance to chemical degradation while maintaining a lightweight structure. The remaining criteria serve as secondary indicators that fine tune the overall performance evaluation. These objective weight results provide a solid foundation for the subsequent TOPSIS method ranking stage, ensuring that the final PMC selection a data driven and unbiased prioritisation of criteria.

The MATLAB script successfully executed all stages of the CRITIC method, generating identical results to those obtained from Microsoft Excel calculations. This consistency confirms the correctness of the algorithm developed and validates the accuracy of the computational approach used. The MATLAB implementation also provides an advantage in term of automation and reproducibility, as it allows for efficient recalculation when new criteria or materials are introduced. Consequently,

MATLAB serves as reliable computational tool for supporting the MCDM process in this stage.

The findings derived from this objective enhanced the existing body of knowledge and provided practical support DM and engineers in the selection of potential PMC. The PDCA cycle, commonly referred to as Deming's cycle, serves a role extending beyond that of a conventional quality management tool. It represented a fundamental framework for continuous improvement processes that was deeply embedded in organisational practices. Owing to its simplicity and structured approach, the PDCA cycle was accessible and suitable for adoption across multiple levels of the organisational workforce.

Within the PDCA framework, the “Act” phase was identified as a critical stage, as it occurred upon project completion and facilitated the reinitiation of the cycle to enable continuous refinement and performance enhancement. In addition, Research Objective 3 provided practical recommendations for practitioners operating in comparable industrial contexts through the analysis of survey findings based on relevant operational characteristics.

This study demonstrated the effectiveness of the integration CRITIC-TOPSIS and PDCA framework as systematic classification and decision support tool for the selection of PMC. Nevertheless, further investigation was required to examine the applicability and efficiency of supplementary DM methods across diverse operational robustness of PMC selection outcomes.

To further promote methodological development, the selection criteria could be expanded to incorporate more specific material attributes, PMC processing duration, comprehensive material testing, completion of ongoing comparative analyses, and alternative PMC treatment methods. Such as expansion would enable a more comprehensive evaluation framework and yield more detailed and reliable material selection results.

4.4.4.2 Results of the TOPSIS Method using MATLAB

Table 4.20 presents the results of polymer matrix ranking using the TOPSIS method computed in Microsoft Excel. The results indicate that PE achieved the highest performance index Pi score = 0.6013, followed by PU with a Pi score 0.5043, and PA,

with 0.4736. These polymers demonstrated the closes proximity to the ideal solution, implying superior overall performance across the evaluated criteria.

In contrast, PC and PP recorded lower performance indices of 0.4581 and 0.4405, respectively, indicating that these materials are less preferable when evaluated collectively against all criteria. The ranking order were PE > PU > PA > PC > PP, reflects the balanced influence of the weighted criteria determined through the CRITIC method in the earlier stage.

The dominance of PE can be attributed to its favourable combination of mechanical performance, low density, and high chemical resistance, which enhances its overall suitability as a polymer matrix (Hersztek and Kopeć 2019; Roiron et al. 2021). PU, though slightly inferior, performed well due to its good elongation at break and toughness, which contribute positively in impact resistance applications. Conversely, PP lower Pi score suggests that it underperformed in key criteria such as tensile strength and modulus, making it less competitive under the current decision structure.

Table 4.20
Result of Polymer Matrix Ranking using the TOPSIS Method in Microsoft Excel

Polymer	**Pi Score**	**Rank**
Polyurethane (PU)	0.5043	2
Polyethylene (PE)	**0.6013**	**1**
Polycarbonate (PC)	0.4581	4
Polypropylene (PP)	0.4405	5
Polyamide (PA)	0.4736	3

Overall, the results validate the reliability of the TOPSIS method in distinguishing among competing polymer matrix by integrating both beneficial and non-beneficial criteria in a systematic and quantitative manner. The findings also align well with reported literature trends, where PE and PU often emerge a leading candidate for polymer composite applications.

To further validate the computational consistency and accuracy of the DM framework, the same dataset and weighting factors were analysed using the MATLAB based TOPSIS method code. The results obtained from MATLAB were identical to those generated in Microsoft Excel, confirming that both platforms yield consistent rankings and performance indices for the evaluated polymer matrix as shown in Figure 4.11. This cross validation strengthens the credibility of the developed computational

model and verifies that the implemented mathematical expression in MATLAB accurately replicate the TOPSIS method algorithm.

Moreover, the use of MATLAB provides a significant advantage in terms of automation, repeatability, and flexibility, allowing rapid re-evaluation of material performance when new data or criteria as introduced (Boll, Vieregg, and Kehrer 2024). Hence, the MATLAB implementation not only enhances the efficiency of the analysis but also supports the robustness of the DM framework established in this stage.

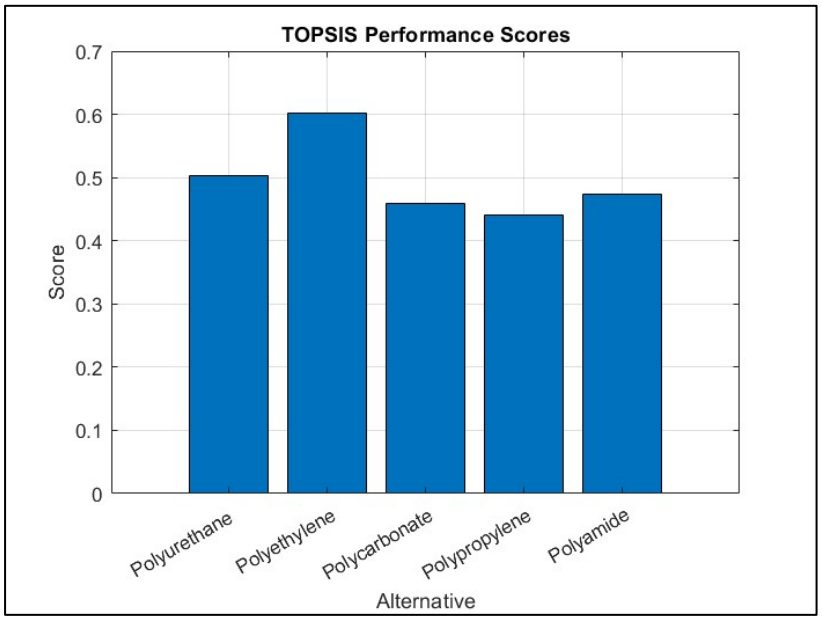


Figure 4.11 Ranking of Polymer Matrix using the TOPSIS Method using MATLAB

4.5 Stage 4: Impact Behaviour

This stage focuses on the evaluation of the impact behaviour of the selected natural fibre composite configuration through explicit dynamic FEA. The objective of this stage is to assess the structural response of the proposed materials under impact loading conditions that are representative of the intended application. Impact behaviour is a crititcal performance indicator for safety related components, as it governs the material ability to absorb energy, limit stress transmission, and prevent catastrophic failure.

In this stage, numerical simulations were conducted to examine key impact related parameters, including stress distribution, deformation characteristics, and energy absorption response. Prior to conducting the impact simulations, a mesh dependency study was performed to ensure numerical stability and result reliability.

The selection of an appropriate element size is essential to balance computational efficiency with solution accuracy, particularly for explicit dynamic analyses where high stress gradients and transient responses are expected.

Accordingly, this stage begins with the determination of an optimal mesh density through element size convergence analysis, followed by detailed evaluation of the impact performance of the selected composite systems.

4.5.1 Selected Element Size

Figure 4.12 illustrates the selected element size conducted to evaluate the dependency of the numerical results on mesh density. The maximum Von Misses stress is plotted against the number of finite elements to assess solution stability and determine an optimal element size for subsequent simulations.

At relatively low mesh densities (below approximately 20,000 elements), the predicted maximum stress exhibits noticeable fluctuations, with values ranging between about 430 MPa and 470 MPa. This oscillatory behaviour indicates insufficient spatial resolution, where stress concentrations are not accurately captured due to coarse discretisation. Such variations are typical in finite element analyses when the mesh is unable to adequately represent localised stress gradients, particularly near geometric discontinuities or contact regions.

As the number of elements increases beyond roughly 25,000 – 40,000, the stress response shows a pronounced rise and subsequently stabilises around 515 – 520 MPa. This trend reflects progressive refinement of the stress field, where improved element resolution leads to more accurate representation of deformation and load transfer within the structure. Importantly, beyond approximately 50,000 – 60,000 elements, further mesh refinement results in negligible changes in the maximum stress value, indicating that the solution has converged.

The vertical dashed line in the graph denotes the selected mesh density of around 60,000 elements, which lies within the convergence plateau. This mesh was chosen as a compromise between numerical accuracy and computational efficiency. The marginal change in stress values beyond this point suggests that further refinement would not provide meaningful improvements in accuracy but would significantly increase computational cost.

Overall, the convergence behaviour confirms that the adopted mesh density is sufficient to ensure reliable and mesh independent results, thereby providing confidence in the validity of subsequent numerical analyses and comparisons presented in this study.

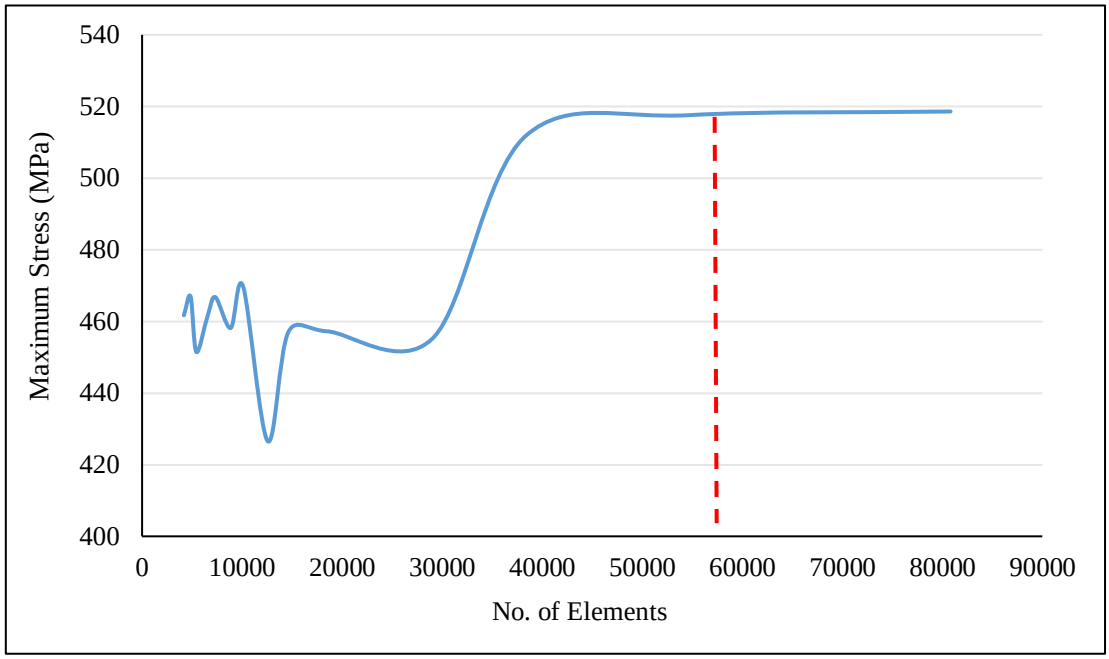


Figure 4.12 Selected Element Size

4.5.2 Numerical Validation

Numerical validation was an essential step in this study to ensure the reliability and credibility of the numerical simulations performed using FEA. Numerical validation referred to the process of verifying numerical results by comparing them with established analytical solutions, experimental data, or well documented findings form previous studies. In computational modelling, numerical validation was conducted to confirm that the adopted modelling assumptions, material properties, boundary conditions, and numerical formulations were capable of accurately representing the physical behaviour of the system under investigation.

The necessity of numerical validation arose from the inherent approximations associated with numerical simulations. Finite element models relied on idealised geometries, simplified material constitutive laws, and discretisation schemes, all of which could influence the predicted stress, displacement, and energy responses. Without validation, the numerical outcomes could have been subject to uncertainty,

potentially leading to inaccurate interpretation or overestimation of the simulation results. Therefore, numerical validation was required to demonstrate that the simulation framework produced results consistent with accepted physical behaviour and previously reported studies.

In this study, numerical validation was performed by comparing the simulated stress and displacement responses with reference data available in the literature under comparable loading and boundary conditions. The comparison showed that the numerical results were in good agreement with the reference values, with deviations remaining within acceptable limits reported in prior studies. This agreement indicated that the developed numerical model was sufficiently accurate and robust for evaluating the impact performance of natural fibre cap toe shoes. Consequently, the validated numerical model provide confidence in the subsequent simulation results and supported the reliability of the conclusions drawn from the impact analysis.

Table 4.21 presents the numerical validation results for the H-VM equivalent stress by comparing the present simulation outcomes with reference values reported in the literature for three metallic materials, namely AISI 1045, S235, and S355. The comparison demonstrated that the present numerical model was able to predict the equivalent stress responses with a reasonable level of accuracy. For AISI 1045, the reference stress value of 858.00 MPa was compared with a simulated value of 811.75 MPa, resulting in an absolute error of 46.25 MPa and a percentage deviation of 5.39%. Although this material exhibited the highest discrepancy among the three cases, the deviation remained within an acceptable range for numerical validation of dynamic or impact related finite element analyses.

In the case of structural steel S235 and S355, the percentage errors were 3.20 % and 6.02% respectively, indicating good agreement between the present simulation and the reference data. The relatively lower error observed for S235 suggested that the numerical formulation, material modelling, and boundary conditions were particularly effective in capturing the stress response of this material. The slightly higher deviation for S355 could be attributed to differences material constitutive assumptions or sensitivity to numerical discretisation, which are commonly reported in finite element based stress predictions. Overall, the validation results confirmed that the numerical model produced stress values that were consistent with established reference data, with all percentage errors remaining below 7%. This level of agreement was considered acceptable for numerical validation and provided confidence in the reliability of the

simulation framework for subsequent impact analyses of natural fibre cap toe shoes, as finite element studies are commonly accepted when percentage deviations between simulation and reference data remain within approximately 5-10% (Pinto et al., 2025).

Table 4.21
Numerical Validation Result for H-VM Equivalent Stress

Material	H – VM Equivalent Stress (MPa)			
	Reference	Present	Error	Percentage
AISI 1045	858.00	811.750	46.250	5.39 %
S235	494.00	509.830	15.830	3.20 %
S355	484.00	513.160	29.160	6.02 %

Table 4.22 presents the numerical validation results for displacement in the Z-direction by comparing the present finite element predictions with reference values for AISI 1045, S235, and S355 steels. Displacement was selected as a critical validation parameter because it directly reflected global structural deformation and energy absorption behaviour under dynamic loading, which are key response indicators in explicit dynamic analyses (Chow and Gliszczynski 2025; Tuo et al. 2019).

Table 4.22
Numerical Validation Result for Displacement in Z Direction

Material	Displacement in Z direction (mm)			
	Reference	Present	Error	Percentage
AISI 1045	4.048	5.555	1.507	37.22%
S235	5.340	5.639	0.299	5.60%
S355	5.440	5.630	0.190	3.48%

For AISI 1045, the reference displacement of 4.048 mm was compared with a present simulated value of 5.555 mm, resulting in an absolute error of 1.507 mm and a percentage of 37.22%. This relatively large discrepancy indicated a reduced agreement for this specific case. Such deviation was likely associated with differences in material constitutive modelling, strain rate sensitivity assumption, or contact definitions, which are known a strongly influence displacement predictions in explicit dynamic simulations. In contrast, the results for S235 and S355 showed significantly better agreement. The percentage errors for S235 and S355 were 5.60% and 3.48%, respectively, indicating close correspondence between the present model and the reference data.

According to established numerical validation guidelines in FEA, displacement errors within 5-10 % are generally considered acceptable for dynamic and impact simulation, particularly when explicit solvers are used and when material nonlinearity and contact interactions are involved (Belytschko et al. 2014). The results for S235 and S355 therefore fell well within commonly accepted validation thresholds and demonstrated that the present modelling approach was capable of accurately capturing global deformation behaviour. Although the deviation observed for AISI 1045 exceeded the typical acceptance range, it remained consistent with findings in the literature where displacement predictions were reported to be more sensitive than stress responses in explicit dynamic analyses due to time step size, contact stiffness, and mesh discretisation affects.

Overall, the displacement validation results confirmed that the numerical model exhibited satisfactory predictive capability for structural steels commonly used as reference materials. In particular, the strong agreement obtained for S235 and S355 provided confidence in the robustness of the modelling strategy, numerical stability, and solver settings adopted in ANSYS Explicit Dynamic. Consequently, the validated framework was deemed suitable for subsequent displacement based impact assessments of natural fibre cap toe shoes designs.

4.5.3 Impact Behaviour of Natural Fibre Cap Toe Shoes

The simulation results presented in Table 4.23 provides a comparative assessment of the impact response of twelve natural fibre materials in term of Von Misses stress and Z-Displacement, with specific reference to the requirements of ISO standards for safety footwear, particularly ISO 20344 and ISO 20345. These standards emphasised the ability of the cap toe shoes to withstand impact loading while maintaining sufficient toe clearance to prevent contact with the worker's toe.

From the displacement perspective, all investigated materials exhibit remarkably consistent values, ranging narrowly between 5.3861 mm and 5.3897 mm, which was consistent with experiment findings in impact testing of natural fibre where displacement response under controlled conditions showed limited variation across repeated specimens with similar geometry and impact loading (Demir 2024). Ijuk exhibited a displacement value of 5.3864 mm, which was among the lowest values recorded. This limited variation indicates that, under the prescribed impact loading

condition, all-natural fibre configurations are capable of controlling deformation within an acceptable range. Importantly, none of the materials demonstrate excessive displacement that would compromise toe clearance, suggesting that all candidates satisfy the fundamental ISO requirement related to deformation control. Consequently, displacement does not serve as the primary discriminating factor among the materials, but rather confirms the structural adequacy of the composite cap toe shoes geometry and boundary conditions adopted in the simulation.

In contrast, the Von Misses stress response shows substantial variation across the materials highlighting clear differences in their ability to distribute and absorb impact energy. Ijuk demonstrated one of the lowest Von Mises stress value, recorded at 42.12 MPa, which was significantly lower than those of the majority of the other natural fibres. This result indicated that Ijuk was superior energy absorption and more effective stress redistribution under impact loading, which are critical attributes for preventing localised failure or cracking in safety cap toe shoes (Siddiqui et al., 2023). These characteristics are particularly desirable in the context of ISO compliant footwear, where repeated or accidental high energy impacts may occur during service life.

Sisal also demonstrates a relatively low stress response of 153.33 MPs, followed by banana at 292.88 MPa, suggesting that these materials may offer acceptable impact resistance, albeit with less margin of safety compared to Ijuk and Coir. Materials such as hemp, Jute, Kenaf, and Bamboo fall within a moderate stress range between approximately 410 MPa and 540 MPa. While these values remain within structurally manageable limits for natural fibre based composite systems, the higher stress levels indicate a reduced capacity for energy dissipation, potentially increasing the risk of damage initiation under severe or repeated impacts.

Conversely, Flax, Pineapple, Ramie, and Abaca exhibit significantly higher Von Misses Stresses, exceeding 660 MPa and reaching up to 967.22 MPa and 409.38 MPa in the case of Ramie and Abaca, respectively. Such elevated stress concentrations are indicative of less favourable impact behaviour and suggest a higher likelihood of material degradation or failure, rendering these fibres less suitable for safety footwear.

Table 4.23
Impact Simulation Results of Natural Fibre for Cap Toe Shoes

No	Material	Von Misses stress (MPa)	Displacement Z (mm)	Stress Interpretation
1	Ijuk	42.12	5.3864	Very low stress
2	Coir	64.07	5.3897	Very low stress
3	Sisal	153.33	5.3890	Low stress
4	Banana	292.88	5.3881	Moderate stress
5	Abaca	409.38	5.3884	Moderate Stress
6	Kenaf	410.15	5.3883	Moderate Stress
7	Hemp	451.00	5.3882	High stress
8	Jute	470.00	5.3883	High stress
9	Bamboo	537.52	5.3861	High stress
10	Flax	660.92	5.3878	Very high stress
11	Pineapple	720.98	5.3878	Very high stress
12	Ramie	967.22	5.3875	Extremely high stress

Overall Ijuk demonstrates the lowest stress response under the simulated impact condition. When these impact simulation results were interpreted in relation to the previous MCDM based material selection outcome, where Ijuk was identified as the optimum natural fibre, a strong consistency was observer. The low Von Mises stress exhibited by Ijuk directly supported its selection as the most suitable candidate for the cap toe shoes. Furthermore, the comparable displacement response confirmed that Ijuk was able to maintain structural stability under impact conditions. Therefore, in accordance with ISO safety footwear requirements and high impacts performance expectations, Table 4.24 serves as a reference legend for interpreting the Von Mises stress values reporter in Table 4.23.

Table 4.24
Stress Interpretation Thresholds Based on Von Mises Stress Values

Stress Interpretation	Von Misses stress Range (MPa)
Very low stress	< 100
Low stress	100 – 200
Moderate stress	200 – 450
High stress	450 – 700
Very high/extremely high stress	>700

Source: Parvathaneni et al. 2022

Table 4.25 presents an integrated assessment of Ijuk and Coir by combining numerical impact performance obtained from analysis with broader material selection considerations. This comparative evaluation was intended to reconcile the differences observed between impact specific simulation results and the outcomes of the material selection framework for protective applications subjected to a 200J impact load, as specified in ISO 20345. The results showed that Ijuk exhibited excellent Von Misses stress behaviour, indicating an enhanced capability to distribute impact induced stresses and reduce localised stress concentrations under dynamic loading. This response suggested a favourable stiffness dominated mechanism that limited excessive stress escalation during impact (Mulenga et al., 2025). Both Ijuk and Coir satisfied the ISO compliant displacement criteria in the Z-direction, confirming that the protective clearance requirement was maintained under the prescribed an impact specific performance, implying that its advantages were primarily confined to stress resistance rather than a comprehensive mechanical response.

Table 4.25
Integrated Assessment of Ijuk and Coir Based on Impact Performance and Material Selection Framework

No	Aspect	Material	
		Ijuk	**Coir**
1	Von Misses stress	Excellent	Very good
2	Displacement Z	ISO compliant	ISO compliant
3	Overall performance	Impact specific	Well balanced

In contrast, Coir exhibited a well balanced impact behaviour by simultaneously maintaining acceptable stress levels, controlled deformation, and effective energy absorption. Such balanced performance has been widely recognised in the literature as essential for materials subjected to high energy, low velocity impact, where safety is governed not only by stress reduction but also by progressive deformation and toughness.

Ijuk possessed favourable impact related characteristics, including excellent stress performance and compliant deformation behaviour/ Although other materials such as Coir exhibited more balanced performance across multiple criteria, the results highlighted Ijuk as a promising and potential material for cap toes shoes where impact resistance is prioritised.

4.5.4 Impact Behaviour of Natural Fibre Reinforced Composite Cap Toe Shoes

Table 4.26 presents the mechanical properties of Ijuk NFRC at different fibre content, ranging from 30% to 60%. The table summarises the variation in composite density, tensile strength, Young Modulus, and elongation at break as a function of fibre content. This analysis aims to investigate the effect of varying natural fibre on the mechanical performance of the composite through FEA.

Table 4.26
Mechanical Properties of Ijuk Natural Fibre Reinfored Composite at Different Fibre Contents

Density Percent of Natural Fibre (E_f)	**Density**	**Tensile Strength**	**Young Modulus**	**Elongation at Break**
30%	1.04	73.73	1.31	350.57
40%	1.09	93.64	1.69	303.26
50%	1.13	113.55	2.08	255.95
60%	1.17	133.46	2.46	208.64

In contrast to strength and stiffness, the elongation at break decreased markedly with increasing fibre content. The elongation at break reduced from 350.57 at 30% fibre loading to 208.64 at 60%. This reduction indicates a loss of ductility as the composite transitions from matrix dominated to fibre dominated behaviour. The presents of stiff natural fibres restrict polymer chain mobility and limits plastic deformation, leading to a more brittle failure mechanism at higher fibre contents. This inverse relationship between stiffness and ductility is a common characteristic of fibre reinforced polymer composites and highlights the inherent trade off between strength enhancement and flexibility (Elfaleh et al., 2023).

Figure 4.13 illustrates the ranking of NFRC based on percentage of density of natural fibre E_f obtained using the CRITIC-TOPSIS approach. The figure compares four fibre content levels, namely 30%, 40%, 50%, and 60% and presents their relative ranking. The results indicate that the composite with 50 % naturl fibre content achieved the highest rank with respect to density performance. This outcome suggests that the decision criterion within the integrated evaluation framework. Although increasing fibre content generally leads to a gradual increase in composite density, the CRITIC-TOPSIS method evaluates density relative to other competing alternatives and their

dispersion, rather than relying solely on absolute values. As a result, the 50% fibre content emerged as the most optimal option under the density-based ranking.

In contrast, the 30% fibre content was ranked lowest, indicating comparatively less favourable density performance within the evaluated range. This lower ranking can be attributed to the reduced contribution of natural fibre to the overall composite structure, which limits the effectiveness of density optimisation in the DM process. The 40% fibre content achived rank 2, while the 60% fibre content was ranked third, reflecting intermediate performance levels between the lowest and highest ranked alternatives.

Overall, Figure 4.13 demonstrates the effectiveness of the CRITIC-TOPSIS approach in differentiating fibre content alternatives based on density considerations. The ranking outcome provides valuable insight for material selection and optimisation, particularly when density is treated as a critical alongside mechanical performance criterion in the composite design process.

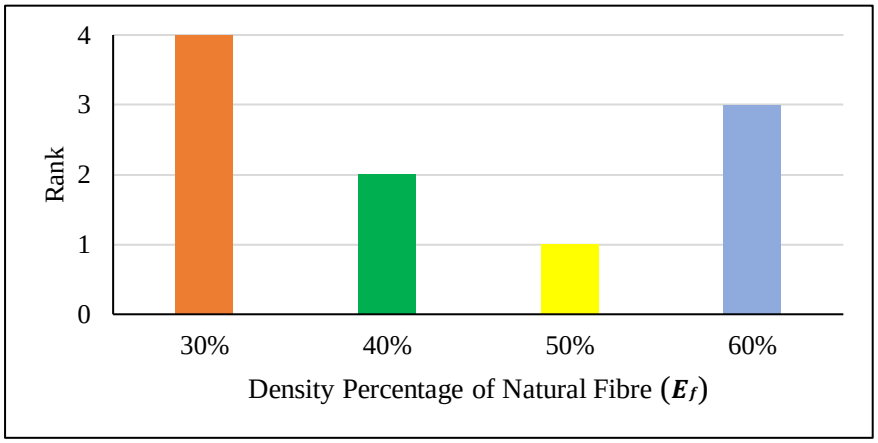


Figure 4.13 Rank Density Percentage of Natural Fibre

Based on the density ranking presented in Figure 4.13, the natural fibre density percentage of 50% achieved the highest rank, indicating its optimal balance between lightweight characteristics and material effectiveness. This outcome supports the selection of the Ijuk based composite configuration evaluated in Table 4.27, as density plays a critical role in governing impact behaviour and structural efficiency.

The impact simulation results in Table 4.27 show that the Ijuk + PE composite exhibited a relatively low on Von Mises stress of 34.615 MPa, accompanied by a controlled displacement of 5.3739 mm udder impact loading. These results suggest that the composite was able to effectively dissipate impact energy while maintaining

structural integrity, which is consistent with the superior density ranking observed at the 50% fibre content in Figure 4.13.

Table 4.27
Impact Simulation Results of Ijuk + PE

No	Material	Von Misses stress (MPa)	Displacement Z (mm)
1	Ijuk + PE	34.615	5.3739

The strong performance of the Ijuk + PE system can be attributed to its low material density, which reduced inertial effects during impact while promoting favourable stress distribution within the structure. These observations are consistent with the ranking trend shown in Figure 4.13, where fibre contents exceeding the optimal level (e.g., 60%) exhibited lower ranking, possibly due to greater stiffness and diminished capacity for energy absorption

Overall, the consistency between the density-based raking in Figure 4.13 and the favourable impact simulation outcomes in Table 4.27 validates the effectiveness of the proposed material selection framework. The results confirm that an optimised Ijuk fibre density not only enhances lightweight performance but also contributes to reduced stress concentration and acceptable deformation behaviour under realistic impact loading conditions.

4.6 Stage 5: Results Deliberation

This stage presents the results and subsequent deliberation arising from the integrated DM framework developed in this study. Building upon the methodological foundation established in the preceding chapters, the focus of this section is to synthesise the outputs obtained form FEA and the CRITIC-TOPSIS MCDM approach in order to identify the most suitable natural fibre material for the intended application. Emphasis is placed on interpreting the results in a systematic and critical manner, rather than merely reporting numerical outcomes.

The FEA results provide detailed insights into the structural response and mechanical feasibility of the shortlisted materials under simulated loading conditions, while the CRITIC-TOPSIS outcomes offer a holistic evaluation based on objectively weighted criteria. By integrating these complementary perspectives, this section

facilitates an informed and robust deliberation process for optimum natural fibre selection.

Accordingly, this section begins with the compilation an assessment of FEA derived performance data, followed by a comparative discussion of material rankings and their qualitative implications. The section concludes with a responded justification of the selected optimum material, thereby ensuring that the final decision is supported by both physics-based simulation evidence and multicriteria evaluation outcomes.

Table 4.28 presents a comparative ranking of potential natural fibre materials as evaluated using FEA and CRITIC-TOPSIS MCDM approach. Although both methods aim to identify optimal materials for the intended application, notable variations in ranking positions as observe, reflecting fundamental differences in methodological focus, evaluation criteria, and underlying assumptions.

Table 4.28
Integrated Ranking Outcomes of Natural Fibre Materials for Optimum Selection using FEA and CRITIC-TOPSIS Method

Rank	**FEA**	**CRITIC-TOPSIS**
1	Ijuk	Ijuk
2	Coir	Ramie
3	Sisal	Coir
4	Banana	Pineapple
5	Abaca	Flax
6	Kenaf	Bamboo
7	Hemp	Hemp
8	Jute	Banana
9	Bamboo	Sisal
10	Flax	Jute
11	Pineapple	Kenaf
12	Ramie	Abaca

The consistency observed at the highest rank, where Ijuk emerges as the top performing material in both FEA and CRITIC-TOPSIS, indicates a strong convergence between structural performance an multi criteria sustainability-based evaluation. Qualitatively, this suggests that Ijuk possesses a balanced combination of mechanical robustness, favourable density characteristics, and functional suitability, while

simultaneously satisfying broader decision criteria such as environmental performance and material efficiency. This alignment reinforces the reliability of Ijuk as a leading candidate and demonstrates the capability of CRITIC-TOPSIS of capture critical performance attributes that are also reflected in physics-based simulations.

However, beyond the first rank, increasing divergence between the two approaches becomes evident. For instance, Coir ranked second in FEA, is positioned third in the CRITIC-TOPSIS results, while Ramie, which occupies the second position in CRITIC-TOPSIS, is ranked last in the FEA assessment. From a qualitative standpoint, this discrepancy highlights the inherent distinction between simulation driven structural evaluation and holistic DM framework. FEA predominantly prioritises mechanical response under applied loading conditions, such as stress distribution, deformation behaviour, and impact resistance, whereas CRITIC-TOPSIS incorporates objective weighting of multiple criteria, including material density, performance trade off and moisture resistance indicators.

Material such as Ramie and Flax, which exhibit relatively high stiffness and favourable specific properties, tend to benefit from the CRITC-TOPSIS framework due to their balanced performance across several criteria. Nevertheless, their lower ranking in FEA suggests potential limitations in energy absorption capability, failure behaviour or manufacturability under explicit dynamic conditions. Conversely, Banana and Sisal, exhibit moderate rankings across both evaluation approaches, indicating a more stable overall performance profile despite not excelling in either structural or multi criteria dimensions.

A notable finding is that Kenaf and Abaca rank lower in the CRITIC-TOPSIS analysis than in the FEA assessment. This suggests that, although they show adequate structural performance, their overall value drops when additional factors like property variability, environmental impact, and supply consistency are considered. This emphasises the need to include non-structural criteria in material selection, especially for sustainability focused applications.

The obtained results were not only interpreted in terms of ranking outcomes but also analysed from a material behaviour and engineering performance perspective. The CRITIC-TOPSIS framework enables a multi dimensional evaluation by capturing both the variability of the data and inter criteria relationships, resulting in a more meaningful interpretation beyond numerical ranking. In this context, the dominate of specific criteria, such as elongation at break and density, reflects the critical importance of

impact energy absorption and lightweight characteristics in cap toe shoes applications. From a mechanical standpoint, materials with higher elongation at break demonstrate superior deformation capacity, which contributes to improved impact resistance and reduced like hood of brittle failure.

Furthermore, the relationships between density and structural efficiency was critically examined, where lower density materials such as Ijuk offer significant advantages in reducing overall shoes mass, thereby improving ergonomic performance without compromising structural integrity. The discussion also considers trade offs among criteria, as materials exhibiting high strength may not necessarily perform well under moisture conditions, highlighting the necessity of a balanced DM framework. Therefore, the in integrated evaluation approach provides not only a ranking but also an in depth understanding of how each material behaves under multiple performance requirements, reinforcing the engineering relevance of the bridge.

Overall, the qualitative comparison between FEA and CRITIC-TOPSIS rankings demonstrates that reliance on a single evaluation method may lead to biased or incomplete material selection decisions. FEA provides indispensable insights into structural integrity and failure reponse, whereas CRITIC-TOPSIS offers a systematic and objective mechanism to balance competing criteria. The observes ranking discrepancies therefore validate the necessity of an integrated DM framework, wherein simulation-based analysis is complemented by MCDM method to ensure both technical feasibility and holistic material suitability.

Table 4.29 summarises the comparative advantages and limitations of FEA and CRITIC-TOPSIS method in the context of material ranking and selection. The discussion highlights that both approaches address distinct yet complementary aspects of the DM process, thereby reinforcing the necessity of an integrated evaluation framework. FEA demonstrates a clear advantage in its ability to provide a physics-based assessment of material behaviour under realistic loading and boundary conditions. Through detailed stress, deformation, and failure analyses, FEA enables direct evaluation of structural feasibility and safety performance, which is particularly critical for load bearing and impact resistant applications. Consequently, materials ranked highly through FEA are those that exhibit superior mechanical integrity and predictable response under simulated service conditions. However, the method is inherently constrained by its narrow focus on mechanical criteria, as it does not explicitly incorporate sustainability related or socio-economic considerations. Furthermore, the

accuracy of FEA outcomes is strongly influenced by modelling assumptions and material idealisation, which may be challenging to justify for NFRC characteristic by heterogeneity and property variability.

Table 4.29
Advantages and Limitations of FEA and CRITIC-TOPSIS in Material Ranking and Selection

Method	Advantages	Limitations
FEA	i. Enables an accurate, physiscs based assessment of structural behaviour under realistic loading and boundary conditions ii. Enables detailed assessment of stress distribution, deformation, and potential failure mechanisms iii. Highly effective for validating mechanical feasibility and safety critical performance iv. Supports parametric and sensitivity analyses for design optimization	i. Focuses primarily on mechanical and structural criteria, neglecting sustainability, environmental, and economic aspects ii. Results are sensitive to modelling assumption material idealisation, mesh dependency, and boundary condition definitions. iii. Limited capability in addressing material variability and heterogeneity inherent in natural fibre composites
CRITIC-TOPSIS	i. Offers a systematic and objective MCDM framework integrating diverse performance indicators. ii. CRITIC weighting reduces subjectivity by considering data contrast and inter criteria correlations iii. Enables holistic evaluation by intergrating mechanical, physical, and sustainability related criteria iv. Effective for early stage material screening and supporting strategies DM	i. Does not accurately represent the physical failure behaviour under actual loading conditions ii. The outcomes are highly dependent on the quality, consistency, and completeness of the input data iii. Rank materials on their overall balanced performance, even if some structural weakness exists

The proposed integrated CRITIC-TOPSIS and FEA framework effectively fulfils the functional requirement of cap toe shoes by systematically addressing key performance criteria, including impact resistance, lightweight characteristics, structural integrity, and environmental sustainability. From a design perspective, cap toe shoes must comply with strict impact standards, requiring material capable of absorbing high energy loads without excessive deformation. The incorporation of elongation at break

and strength related criteria within the CRITIC-TOPSIS framework directly ensures that selected materials possess adequate energy absorption and load bearing capacity.

In addition, the inclusion of density as a key criterion supports the development of lightweight solutions, which is essential for reducing user fatigue. The ranking results indicate that the selected material, Ijuk, achieves an optimal balance between low density and mechanical performance, thereby meeting the dual requirement of protection and comfort.

Furthermore, the integration of FEA provides a critical validation layer by simulating real world impact conditions. The FEA results demonstrate that the selected composite material exhibits low stress concentration and acceptable displacement under impact loading, confirming its structural reliability for cap toe shoes applications. This alignment between MCDM ranking and FEA validation highlights the robustness of the proposed framework.

Finally, the framework incorporates sustainability considerations through the selection of natural fibre materials, which are biodegradable and environmentally friendly. This directly supports the development of green protective equipment while maintaining compliance with safety requirements. Therefore, the proposed framework fulfils both the engineering and environmental requirements of cap toe shoes, providing a comprehensive and reliable decision support tool for material selection.

CHAPTER 5
CONCLUSION

5.1 Conclusion

The aim of this study was focused on developing a systematic decision support framework for prioritising natural fibre reinforce composite materials by integrating CRITIC-TOPSIS MCDM method with FEA. The research emphasised early stage material evaluation, where potential material selection is crucial in determining structural performance, weight efficiency, and sustainability outcomes. Mechanical performance was rigorously assessed through FEA. The results demonstrate that the proposed integrated framework effectively improves the reliability, consistency, and robustness of material selection by simultaneously considering mechanical, physical, and sustainability related criteria. Furthermore, the framework supports systematic comparison and rational prioritisation of alternative materials, thereby reducing uncertainty in early stage design decisions. Overall, the findings confirm that the proposed method provides a practical and reliable tool for material screening and strategic decision support, fulfilling the Research Objective and validating its effectiveness for sustainable composite material selection. The research findings are summarised below in accordance with the precise objectives outlined.

a) Objective 1: To construct a framework for prioritising natural fibre composite materials through the CRITIC-TOPSIS MCDM approach

The present study a developed a DM framework for prioritising natural fibre composite materials by integrating the CRITIC and TOPSIS methods. Twelve natural fibres were assessed against nine mechanical and manufacturing related criteria. The results demonstrate that the framework is capable of effectively differentiating among candidate natural fibres despite variability in mechanical characteristic, leading to a consistent rational prioritisation outcome. More importantly, the study verifies that the proposed framework enhances decision transparency, improve robustness against bias, and support reproducible material evaluation under multiple conflicting criteria. From a broader perspective, the developed CRITIC-TOPSIS framework contributes a structured and generalisable decision support tool for early stage composite material

selection, particularly in situations where uncertainty and multidimensional performance requirements are present.

b) Objective 2: To perform a material selection for natural fibres material in the cap toe shoes design using CRITIC-TOPSIS MCDM approach

The findings corresponding to objective 1 provide a systematic guideline that underscores the importance of implementing the CRITIC-TOPSIS method in the material selection process. The findings confirm that the proposed approach reduces subjectivity, improves decision consistency, and enables rational evaluation of competing material options under multiple criteria. Importantly, the selected natural fibre material exhibits favourable overall performance for cap toe shoes application, indicating the practical applicability of the developed framework. Therefore, it can be concluded that the CRITIC-TOPSIS based material selection approach enhances the reliability and effectiveness of natural fibre selection for NFRC cap toe shoes while supporting more informed and systematic engineering DM.

c) Objective 3: To investigate a PMC selection for cap toe shoe design integrating the PDCA with the CRITIC-TOPSIS approaches, and MATLAB coding

The suitable thermoplastic matrix for NFRC intended for cap toe shoes applications were selected through an integrated PDCA and CRITIC-TOPSIS framework. The resulting outcomes were derived from the systematic integration of qualitative and quantitative DM approaches across two complementary methodologies. The results demonstrate that the proposed framework improve decision reliability, reduces subjectivity, and enhances transparency through a structured and reproducible computational implementation. Furthermore, the selected PMC exhibits balanced mechanical and durability performance, supporting its suitability for cap toe shoes design. Overall, the study verifies that integrating PDCA with CRITIC-TOPSIS and computational modelling strengthens the effectiveness and consistency of PMC selection, providing a dependable decision support foundation for advanced composite material design.

d) Objective 4: To simulate finite element models of NFRC cap toe shoes through explicit impact analysis using ANSYS workbench

The results demonstrated that the selected composite materials exhibited satisfactory impact resistance, controlled deformation, and effective energy absorption under impact loading. The simulations response demonstrates that the selected

composite system is capable of maintaining structural integrity, limiting deformation, and effectively absorbing impact energy under dynamic loading conditions, indicating its capability to satisfy functional safety requirements. Beyond performance verification, the study confirms the effectiveness of computational modelling as a predictive tool for evaluation impact response and reducing dependence on extensive experimental testing. Importantly, the results support the feasibility of utilising NFRC as a lightweight and sustainable alternative to conventional metallic cap toe shoes materials. Overall, the objective is achieved as the simulation framework establishes a validated basis for understanding impact performance and supports informed structural design of composite based safety footwear.

Therefore, it can be concluded that the proposed framework not only strengthens the reliability of NFRC prioritisation but also establishes a methodological foundation for objective and systematic material selection in advanced composite engineering applications.

5.2 Recommendations for Future Work

Based on the results obtained form this study, several recommendations for future study are listed below:

1. To conduct a study on LCA and Life Cycle Cost Analysis (LCCA), while sustainability aspects were considered qualitatively, future work should quantitatively integrate full LCA and LCCA into the DM framework. This would enable holistic evaluation of environmental and economic trade off across the product life cycle.
2. To conduct a study on experimental validation of numerical and MCDM outcomes, to validate both the CRITIC-TOPSIS ranking results and the finite element simulation outcomes. Physical impact, compression, and penetration tests in accordance with relevant safety footwear standards (EN ISO 20345 or ASTM F2413) would strengthen then credibility of the proposed framework and reduce reliance on purely numerical assumptions.
3. To conduct a study in extension to other safety critical applications, to proposed integrated CRITIC-TOPSIS and FEA framework can be extended to other safety critical components such as helmets, automotive interior panels, or protective sports equipment. Such extensions would demonstrate

the generalisability and scalability of the methodology beyond cap toe shoes applications.

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APPENDICES

APPENDIX 1

CRITIC METHOD

Step 2: Normalisation of the decision matrix

$$\overline{x_{ij}} = \frac{x_{ij} - x_j^{worst}}{x_j^{best} - x_j^{worst}} \quad (2.1)$$

For example, the normalised value was calculated as, $\bar{x}_{ij}$ = (20-15)/(58-15) = 0.1163. The complete normalised decision matrix was presented in Table 4.3.

Table 5.1
Normalisation of the Decision Matrix

	Diameter (µm)	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**
Abaca	0.1163	0.7143	0.8824	0.7447	0.0339	0.7353
Bamboo	1.0000	0.2418	0.7727	1.0000	0.1328	0.0000
Coir	0.0814	0.0000	0.0000	0.0000	1.0000	0.3265
Jute	0.0000	0.3846	0.7362	0.8564	0.0000	0.9044
Kenaf	0.2093	1.0000	0.8646	0.7447	0.1412	0.5588
Sisal	0.2791	0.6044	1.0000	0.2021	0.0085	1.0000

Step 3: Calculation of the standard deviation of each criterion.

$$s_j = \sqrt{\left(\frac{\sum_{i=1}^{m} x_{ij} - \bar{x_j}}{m-1}\right)^2} \quad (2.2)$$

For illustration. The mean normalised values was computed as, $\bar{x}$ = (0.1163+1+0.0814+0+0.2093+0.2791)/6 = 0.2810. Subsequently, the standard deviation for the criterion was calsulated as, $s_j = \sqrt{((0.1163 - 0.2810)^2 + (1 - 0.2810)^2 + (0.0814 - 0.2810)^2 + (0 - 0.2810)^2 + (0.2093 - 0.2810)^2 + (0.2791 - 0.2810)^2)/(6-1)}$ = 0.3655. The complete standard deviation values for all criteria were presented in Table 4.4.

Table 5.2
Distribution of each Criteria Standard Deviation

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
Abaca	0.1163	0.7143	0.8824	0.7447	0.0339	0.7353
Bamboo	1.0000	0.2418	0.7727	1.0000	0.1328	0.0000
Coir	0.0814	0.0000	0.0000	0.0000	1.0000	0.3265
Jute	0.0000	0.3846	0.7362	0.8564	0.0000	0.9044
Kenaf	0.2093	1.0000	0.8646	0.7447	0.1412	0.5588
Sisal	0.2791	0.6044	1.0000	0.2021	0.0085	1.0000
STDEV	**0.3655**	**0.3567**	**0.3596**	**0.3963**	**0.3873**	**0.3759**

Step 5: Determination of criteria weight

$$w_j = \frac{c_j}{\sum_{j=1}^{n} c_j} ; j = 1, \dots, n \tag{2.3}$$

For illustration, the information content for a criterion was computed as, $c_j = \sum_{j=1}^{n} c_j$= ((1-1) + (1-(-1.1914)) + (1-0.2122) + (1-0.4168) + (1-(-0.1694) + (1-(-0.7022)) x 0.3655 = 1.9863. The total information contect across all criteria was, $\sum c_j$ = 1.9863 + 7.5357 + 1.4437 + 3.0608 + 2.0520 = 11.8920. Accordingly, the weight of the criterion was obtained as, w_j = 1.9863/11.8920 = 0.1670. The complete weighting results for all selected performance criteria were presented in Table 4.6.

Table 5.3
Determine the Weight of the Selected Criteria

	Major Criteria	C_j.	W_j.
Diameter (µm)	5.4341	*1.9863*	0.1670
Length (mm)	4.3049	7.5357	0.1291
Tensile Strength (MPa)	4.0151	1.4437	0.1214
Young's Modulus (GPa)	4.5756	1.8135	0.1525
Elongation at Break (%)	7.9031	3.0608	0.2574
Cellulose (%)	5.4586	2.0520	0.1725
TOTAL		**11.8920**	**1.0000**

APPENDIX 2

TOPSIS METHOD

Step 2: Normalisation of the decision matrix.

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^{m} {f_{ij}}^2}} ; j = 1, 2, \dots, m; i = 1,2, \dots, n \quad (2.4)$$

For illustration, the sum of square was calculated as, $\sum {f_{ij}}^2 = (20^2) + (58^2) + (18.5^2) + (15^2) + (24^2) + (27^2) = 5636.25$. The corresponding normalised value was then obtained as, $r_{ij} = 20/\sqrt{5636.25} = 0.2664$. The complete normalised decision matrix were presented in Table 4.8.

Table 5.4
Normal Decision Making Matrix

	Diameter (µm)	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**
WEIGHT	**0.1670**	**0.1291**	**0.1214**	**0.1525**	**0.2574**	**0.1725**
Abaca	0.2664	0.4813	0.4538	0.4425	0.1346	0.4360
Bamboo	0.7726	0.2701	0.4132	0.5720	0.2158	0.2528
Coir	0.2464	0.1621	0.1278	0.0648	0.9281	0.3342
Jute	0.1998	0.3340	0.3997	0.4991	0.1067	0.4782
Kenaf	0.3197	0.6090	0.4472	0.4425	0.2227	0.3921
Sisal	0.3596	0.4322	0.4972	0.1673	0.1137	0.5020

Step 3: Construction of the weighted normalised decision

$$v_{ij} = w_i \, x \, r_{ij} ; j = 1,2, \dots, j; i = 1,2, \dots, n \quad (2.5)$$

For illustration, a weighted normalised value was computed as, $v_{ij} = 0.2664x0.1670 = 0.445$. The complete weighted normalised decision matrix was presented in Table 4.9.

Table 5.5
Decision Matrix with Weights and Normalisation

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
WEIGHT	**0.1670**	**0.1291**	**0.1214**	**0.1525**	**0.2574**	**0.1725**
Abaca	0.0445	0.0622	0.0551	0.0675	0.0346	0.0752
Bamboo	0.1290	0.0349	0.0502	0.0872	0.0555	0.0436
Coir	0.0412	0.0209	0.0155	0.0099	0.2389	0.0577
Jute	0.0334	0.0431	0.0485	0.0761	0.0275	0.0825
Kenaf	0.0534	0.0786	0.0543	0.0675	0.0573	0.0676
Sisal	0.0601	0.0558	0.0604	0.0255	0.0293	0.0866

Step 4: Determination of the positive ideal and NISs and degree of closeness

$$A^* = \left\{\left(\max_i v_{ij} \,\middle|\, j \in C_b\right),\ \left(\min_i v_{ij} \,\middle|\, j \in C_c\right)\right\} = \left(v^*{}_j \middle| j = 1, 2, \dots, m\right)$$
$$A^- = \left\{\left(\min_i v_{ij} \,\middle|\, j \in C_b\right),\ \left(\max_i v_{ij} \,\middle|\, j \in C_c\right)\right\} = \left(v^-{}_j \middle| j = 1, 2, \dots, m\right) \quad (2.6)$$

In this example the positive ideal value was identifires as A^* = 0.1290, whereas the negative ideal was A^- = = 0.0334.

Table 5.6
Compared to Negative Ideal Solutions and Positive Ideal Solutions

	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)
A^*	0.1290	0.0786	0.0604	0.0872	0.2389	0.0866
A^-	0.0334	0.0209	0.0155	0.0099	0.0275	0.0436

Step 5: Determination of separation measures

$$S_i^* = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^*\right)^2} \ , j = 1, 2, \dots, m$$

Similarly, the distance from negative ideal solution is:

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^*\right)^2} \ , j = 1, 2, \dots, m \quad (2.7)$$

Where S^* and S^- are distance from the target alternative, *i* to the worst and best conditions alternatives.

For the illustraion, the separation distance from positive ideal was computed as,

$$S_i^* = \sqrt{\begin{matrix}(0.445-0.1290)^2+(0.0622-0.0786)^2+(0.0551-0.0604)^2+\\(0.0675-0.0872)^2\\+(0.0346-0.2389)^2+(0.0752-0.0866)^2\end{matrix}}$$

= 0.2229

Similarly, the separation distance from the positive ideal silution was computed as,

$$S_i^- = \sqrt{\begin{matrix}(0.445-0.0334)^2+(0.0622-0.0209)^2+(0.0551-0.0155)^2+\\(0.0675-0.0099)^2\\+(0.0346-0.0275)^2+(0.0752-0.0436)^2\end{matrix}}$$

= 0.0881.

The complete separation measure for all alternative were presented in Table 4.11.

Table 5.7
Compared to Separation Measure for each Performance Criterion

	Abaca	**Bamboo**	**Coir**	**Jute**	**Kenaf**	**Sisal**
S_i^*	0.2229	0.1936	0.1410	0.2353	0.1987	0.2303
S_i^-	0.0881	0.1316	0.2120	0.0865	0.1001	0.0777

Step 6: Calculation of the relative closeness to the ideal solution

$$RC_i^* = \frac{S_i^-}{S_i^* + S_i^-}, 0 \leq RC_i^* \leq 1, \qquad i = 1, 2, \ldots, m \tag{2.8}$$

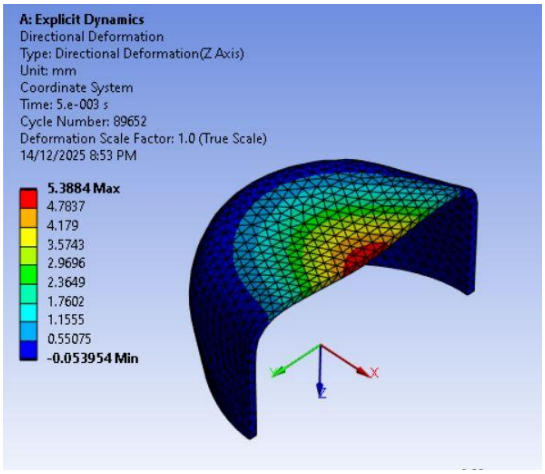
For the illustration, the relative closeness value was computed as, Pi = 0.0881/(0.2229+0.0881)=0.2832.

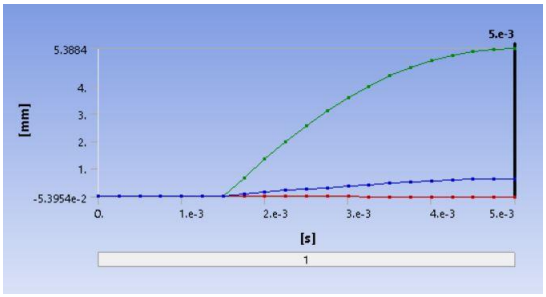
Table 5.8
Relative Closeness to the Ideal Solution for each Performance

	Abaca	**Bamboo**	**Coir**	**Jute**	**Kenaf**	**Sisal**
Pi	0.2832	0.4047	0.6006	0.2688	0.3351	0.2523

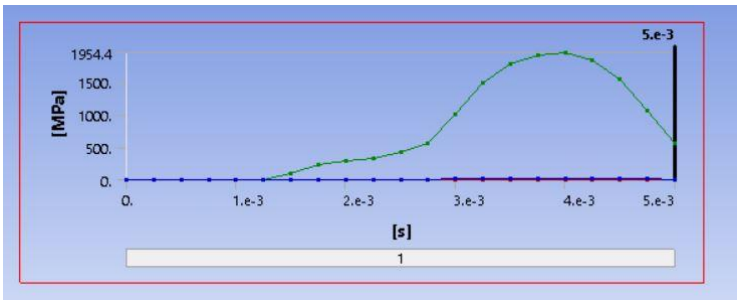
APPENDIX 3

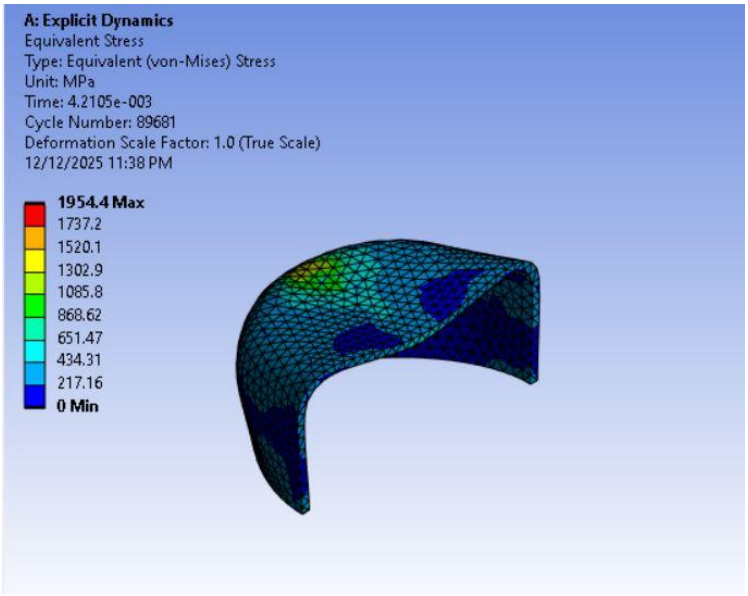
Result Deformation Abaca



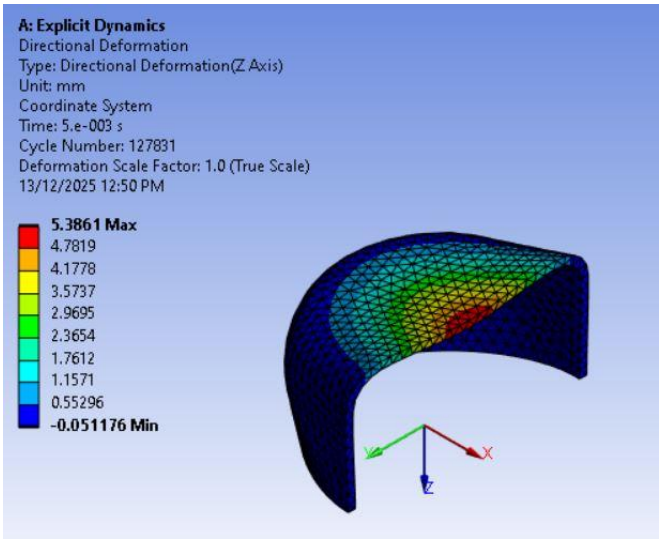


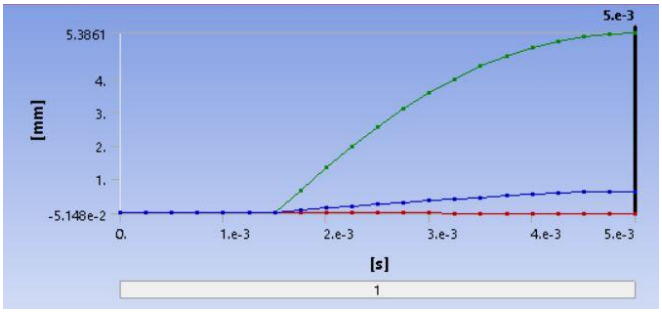
Result Von Misses Abaca



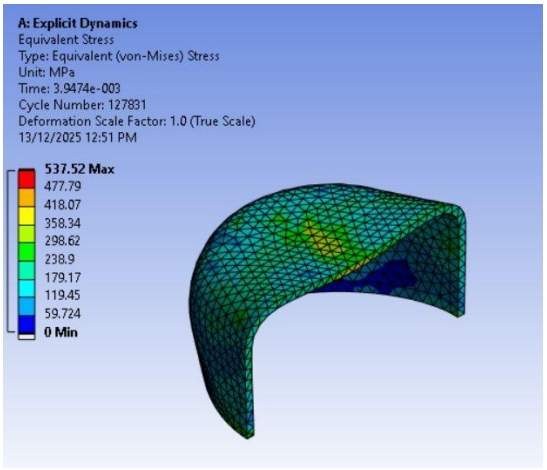


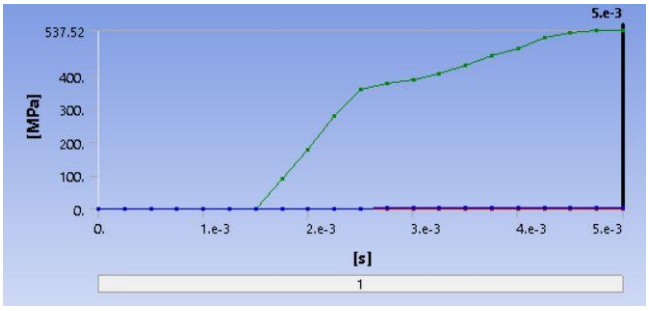
Result Deformation Bamboo



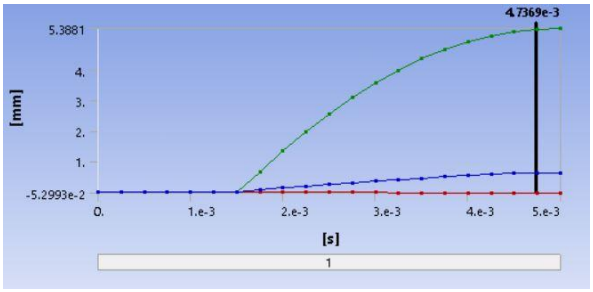


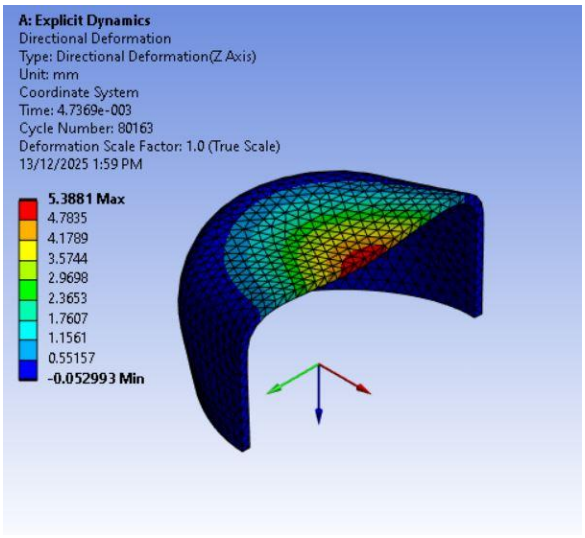
Result Von Misses Bamboo



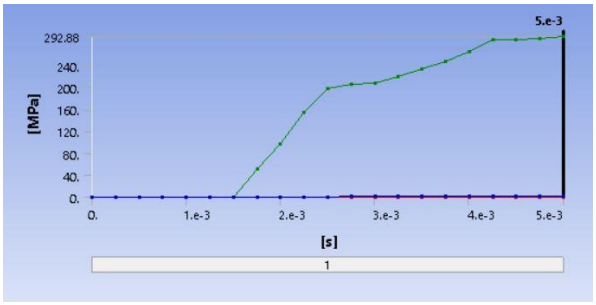


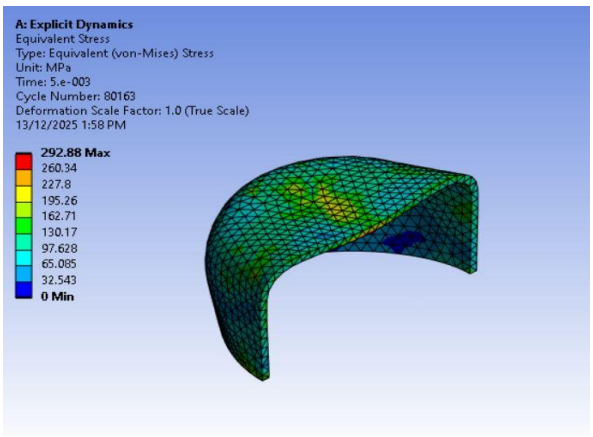
Result Deformation Banana



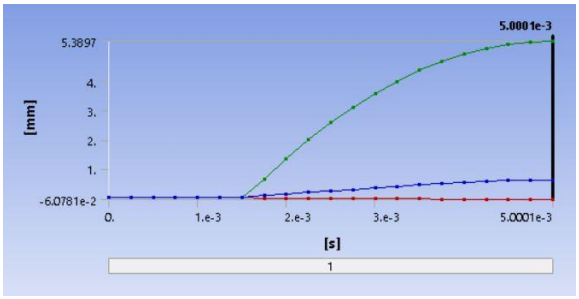


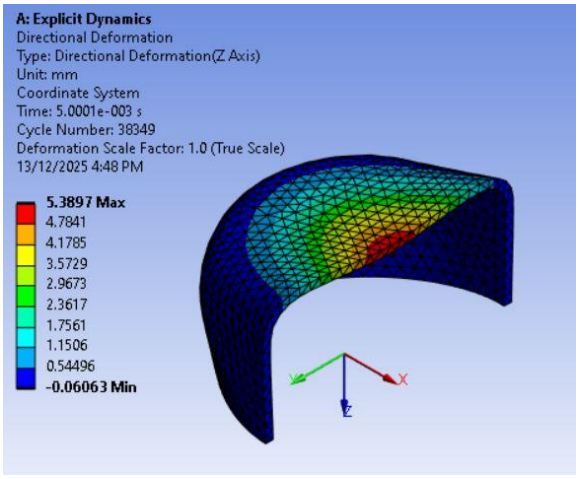
Result Von Misses Banana



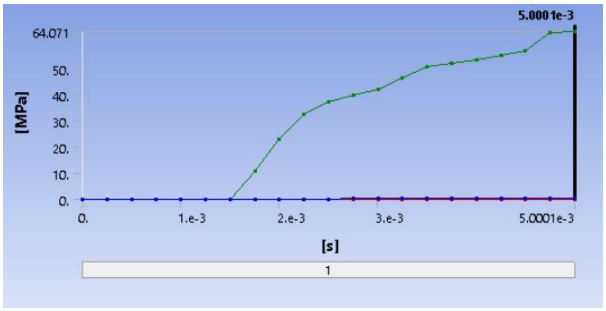


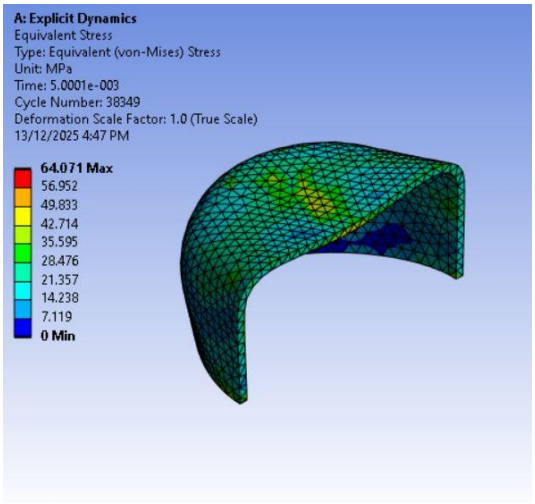
Result Deformation Coir



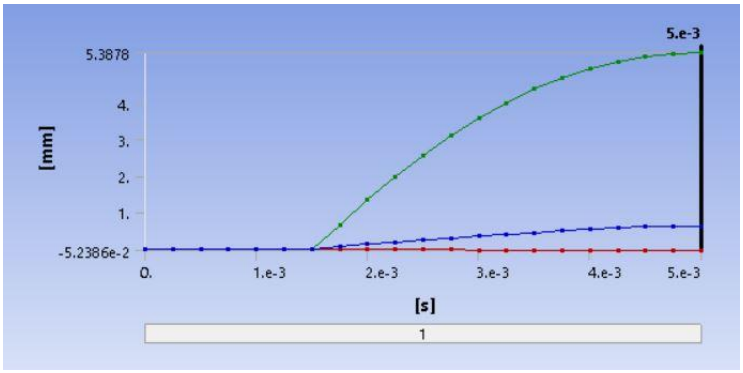


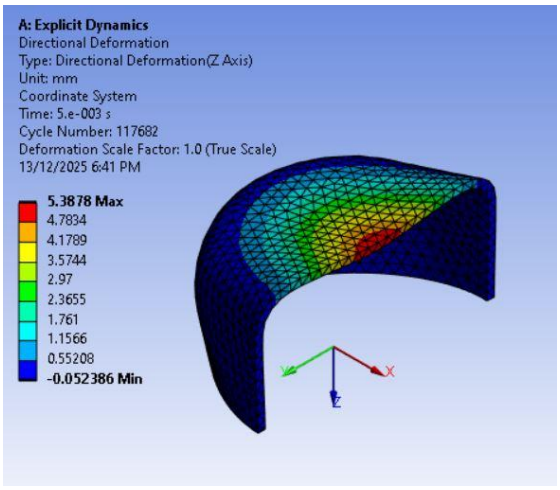
Result Von Misses Coir



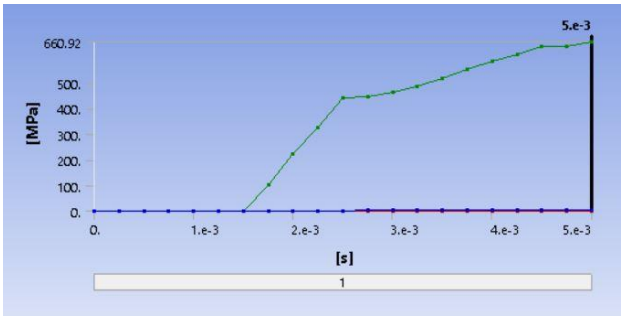


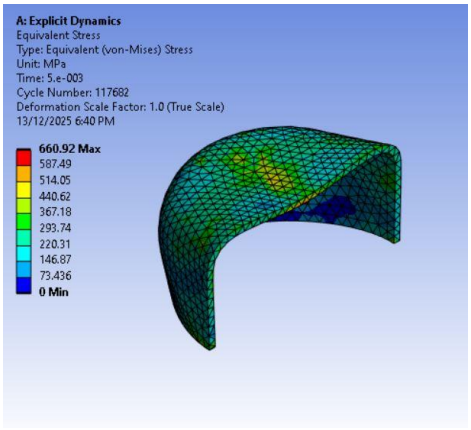
Result Deformation Flax



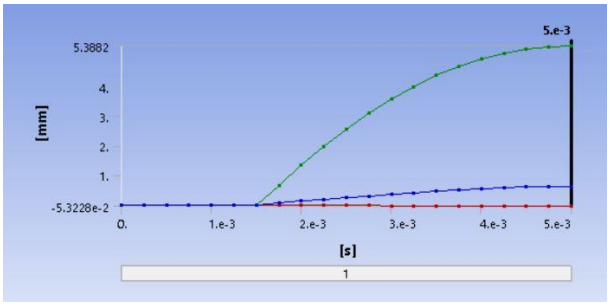


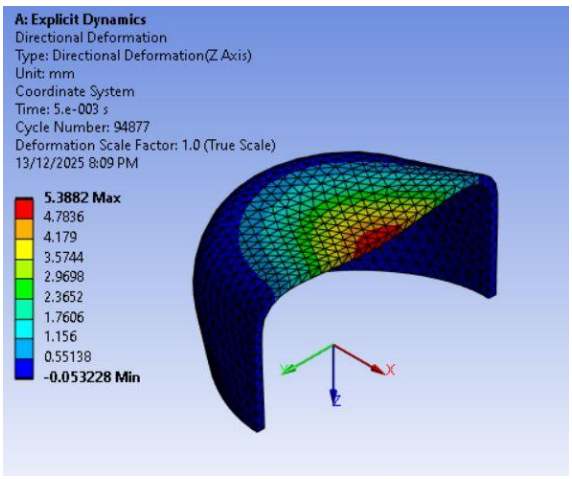
Result Von Misses Flax



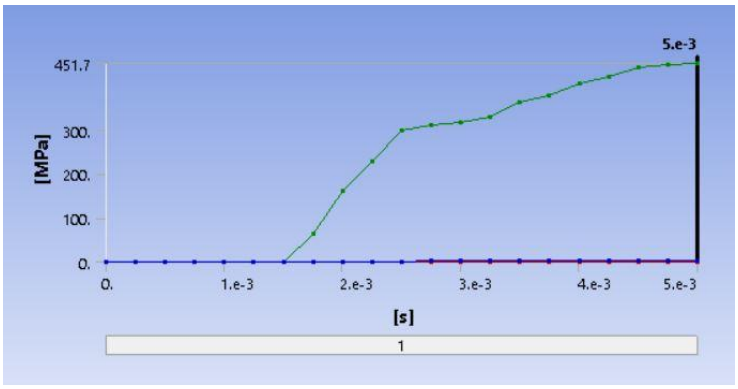


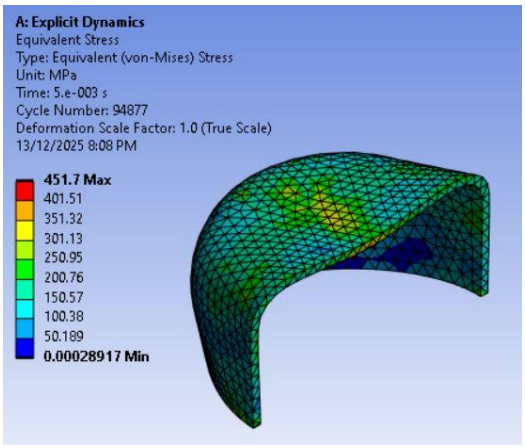
Result Deformation Hemp



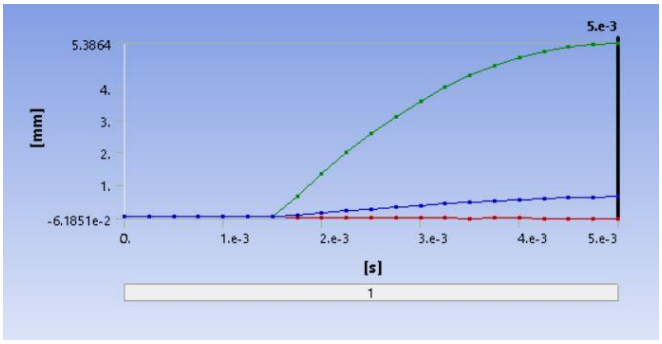


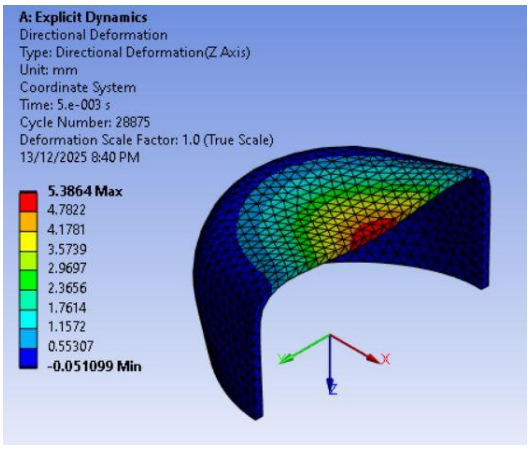
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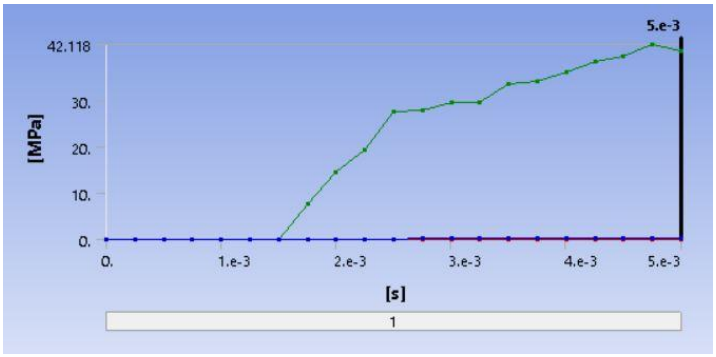


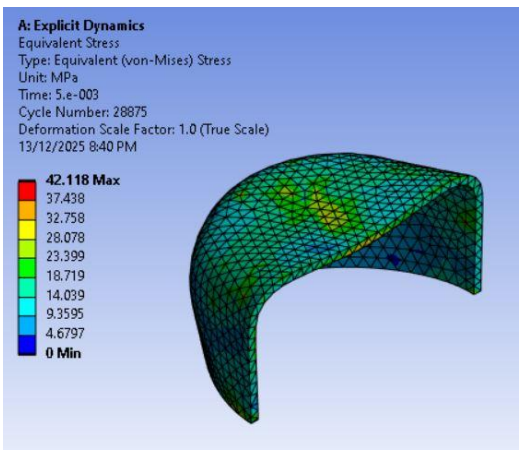
Result Deformation Ijuk



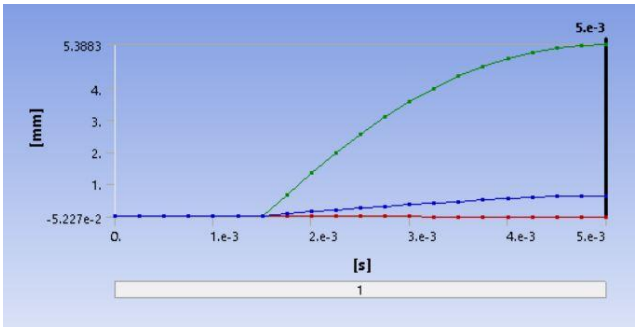


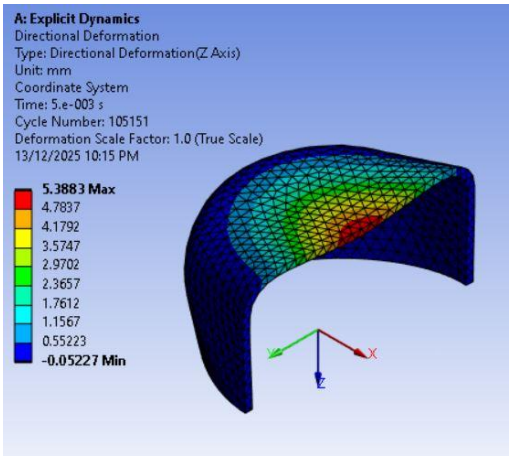
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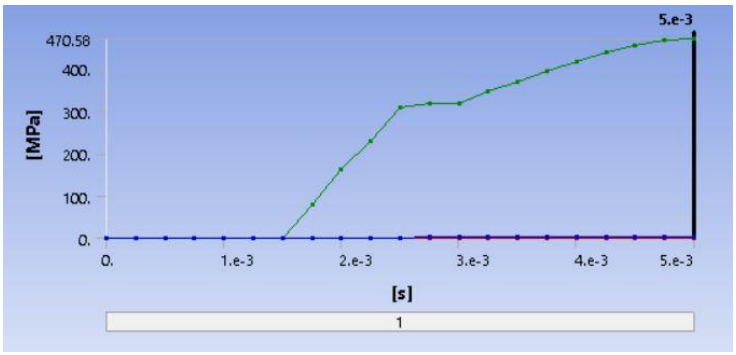


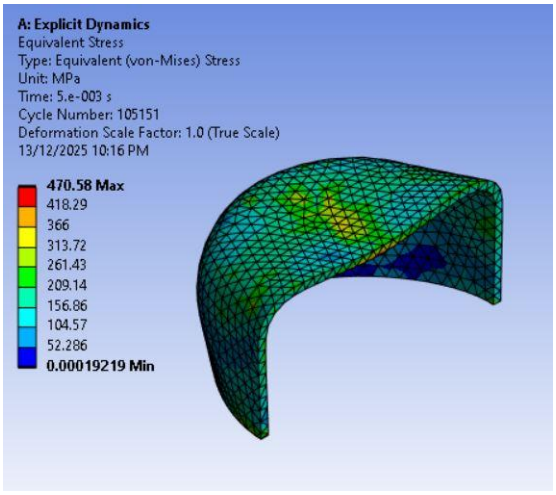
Result Deformation Jute



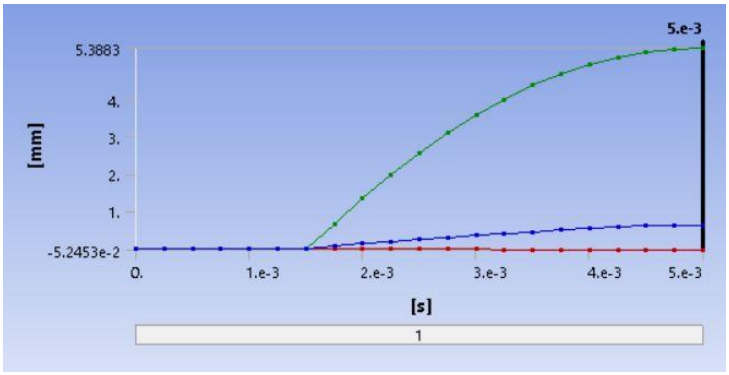


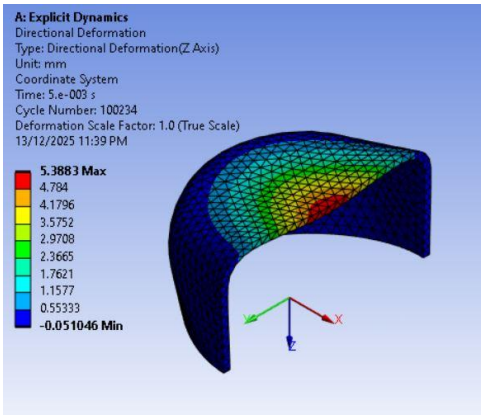
Result Von Misses Jute



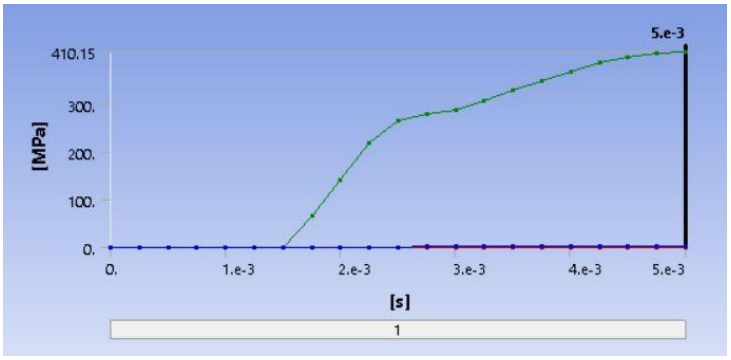


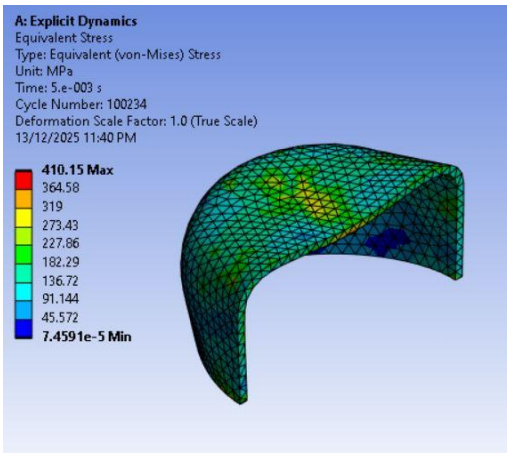
Result Deformation Kenaf



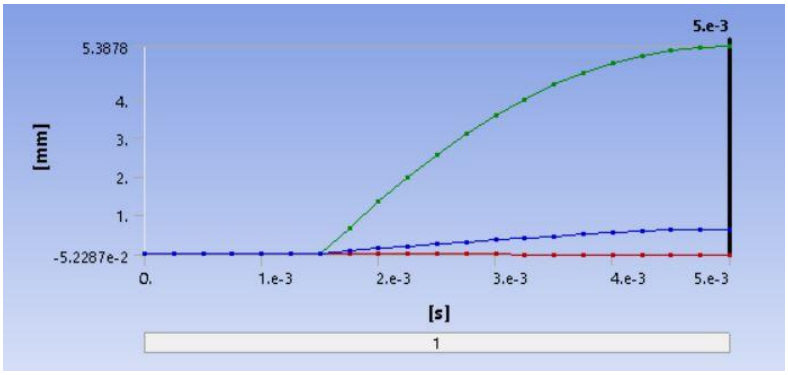


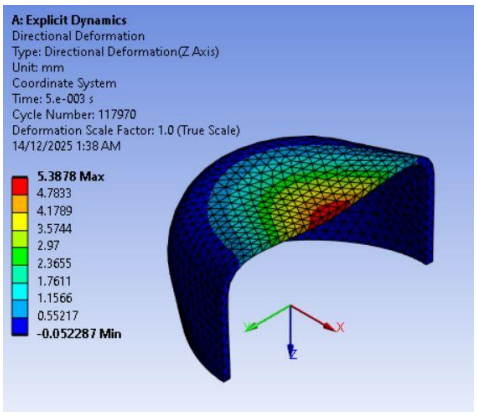
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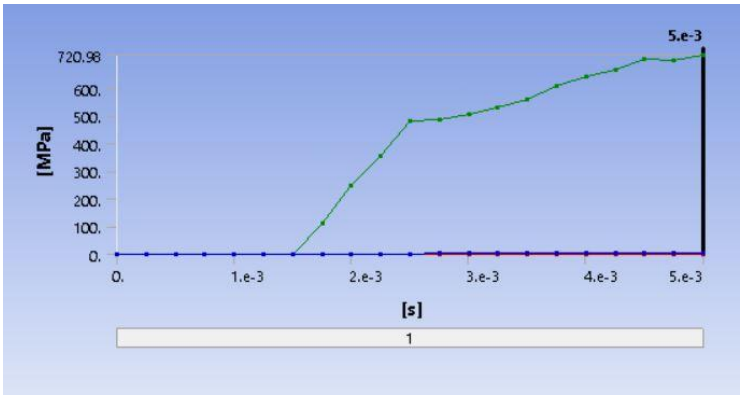


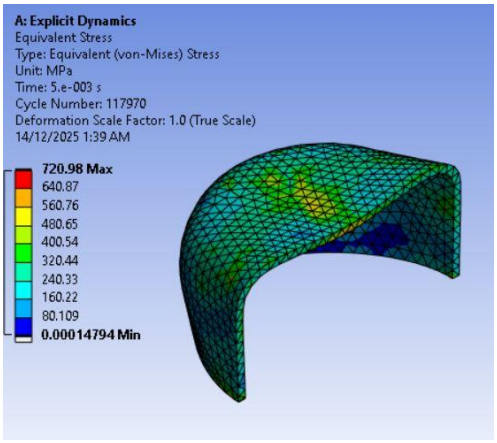
Result Deformation Pineapple



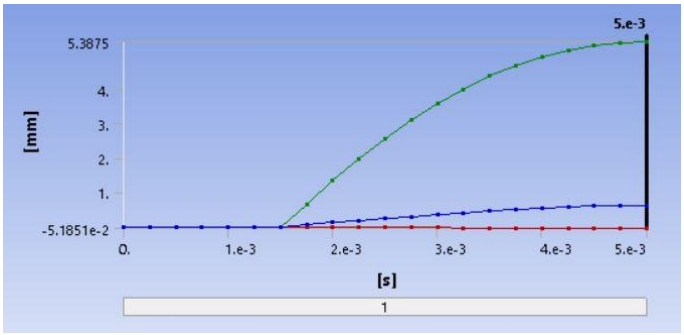


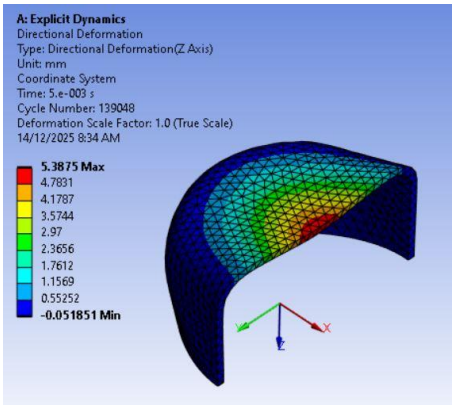
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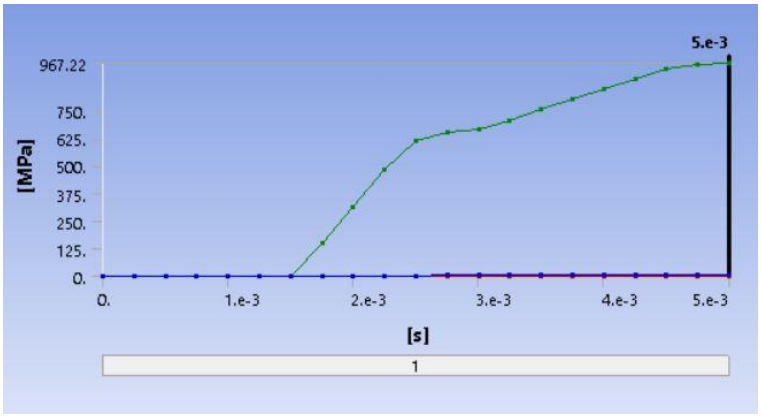


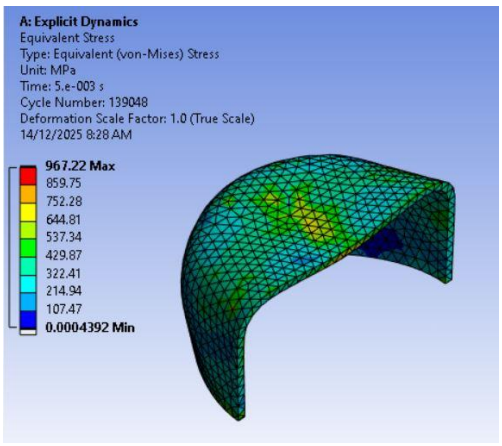
Result Deformation Ramie





Result Von Misses Ramie





AUTHOR'S PROFILE



Mohd Hidayat bin Ab Rahman obtained a Diploma in Tool and Die Technology in 2008 from Kolej Kemahiran Tinggi MARA Balik Pulau, Pulau Pinang, Bachelor of Engineering Technology (Hons.) in Tool and Die in 2011 from Institute Product Design and Manufacturing (IPROM), UniKL, MSc in Innovation and Engineering Design (2013) from Universiti Putra Malaysia. His first job is as an Application Engineer and currently he is working at Universiti Teknikal Malaysia Melaka (UTeM) as senior lecturer. In 2022, he started his PhD study in the field of Mechanical Engineering at Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), Shah Alam.

LIST OF PUBLICATIONS:

Ab Rahman, M. H., Abdul Rahman, S.M., Jumaidin, R., and Mahmud, J. (2024). "A Framework for Prioritising the Performance Criteria of Natural Fibre Composite Materials: Incorporation of CRITIC-TOPSIS Method," *Pertanika Journal of Science and Technology, 32*, 6, 2679-2698. DOI: 10.47836/pjst.32.6.14. {Scopus/WoS ESCI}

Ab Rahman, M.H., A., Mahmud, J., Jumaidin, R., and Abdul Rahman, S.M. (2025). "Integrated CRITIC-TOPSIS and Monte Carlo Sensitivity Analysis for Optimal Various Natural Fibre Selection in Sustainable Building Insulation Composites to Support the Sustainable Development Goals (SDGs)," *ASEAN Journal of Science and Engineering, 5*, 2, 231-260, DOI: 10.17509/ajse.v5i2.85614. {Scopus}

Ab Rahman, M. H., Mahmud, J., Rahman, S. M. A., and Jumaidin, R. (2025). "The

Application CRITIC-TOPSIS Method Integrated with PDCA Cycle in Solving Material Selection of Polymer Matrix material for Natural Fibre Composites in Cap Toe Shoes," In *Journal of Physics: Conference Series*, 2933, 1, 012009, DOI: 10.1088/1742-6596/2933/1/012009. {Scopus}

INNOVATION AWARD:

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