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# ResearchOptimizing Ratios for Eco-Friendly Apparel Production- Pineapple and Cotton Blend

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## Abstract
This study investigates the mechanical and comfort properties of blended yarns comprising Pineapple Fiber (PAF) and Organic Cotton. As the textile industry shifts toward sustainability, PAF emerges as a high-strength, agro-waste alternative. Using a blended fiber, we optimized blending ratios (20:80, 30:70, and 40:60) and twist factors. Results indicate that a 30:70 PAF/Cotton blend offers the optimal balance between tensile strength, Comfort and moisture management. This study provides a strategic framework for scaling PAF-based organic apparel for kids wear in the global market.

**Keywords:** Organic Apparel, exceptional tensile, land-intensive crop, Sustainable Textiles; Tri-blended Yarn.

*Image: Primary to last phase of the agro fiber to clothing*
*Sources: pineapple-fiber-fabric-clothing.html*

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## Introduction
The contemporary textile industry is at a critical crossroads, currently accounting for approximately 8–10% of global carbon emissions and 20% of industrial water pollution worldwide. While natural fibers like cotton have historically dominated the organic apparel sector, their environmental pedigree is increasingly scrutinized. Conventional cotton cultivation requires approximately 10,000 to 20,000 liters of water to produce cotton one kilogram of fiber, alongside heavy pesticide utilization that degrades soil health. Even organic cotton, while eliminating synthetic inputs, remains a land-intensive crop that competes with food security.
In this context, the exploitation of agricultural residues specifically Pineapple Fiber (PAF) presents a transformative opportunity for a circular bio-economy. PAF is derived from the leaves of the *Ananas comosus* plant, a major tropical fruit crop. Globally, pineapple production generates millions of tons of waste annually; these, damage and spoil pulp & leaves are typically burnt or left to rot, releasing greenhouse gases [1].
Unlike primary fiber crops, PAF is a secondary by product, meaning its production requires zero additional land, irrigation, or fertilizer beyond what is already used for fruit cultivation. Chemically, PAF is a multi-cellular, lignocellulosic fiber characterized by a high cellulose content (up to 82%), which contributes to its exceptional tensile strength and stiffness compared to other bast fibers like jute or coir. Despite its superior mechanical properties, the integration of PAF into the apparel mainstream has been hindered by its inherent physical characteristics. Pure PAF is characterized by:
- ✓ **High Flexural Rigidity:** Making it harsh to the touch and difficult to drape.
- ✓ **Low Cohesion:** Presenting significant challenges during the high-speed ring spinning processes.
- ✓ **Coarseness:** Leading to reduced yarn evenness and higher breakage rates.

To mitigate these limitations, blending with organic cotton serves as a strategic intervention. Blending allows for a hybridization of properties, where the strength of PAF is tempered by the softness and elasticity of cotton, resulting in a fabric that is both high-performance and commercially viable for the garment industry [2].

## Research Vision

This research addresses the critical need for a standardized Optimization Matrix for PAF/Cotton blends. While previous studies have explored the general feasibility of PAF, there is a lack of rigorous data on how specific blending parameters namely the fiber ratio and twist factors impact the lifecycle, strength and comfort metrics of organic apparel. These studies try to found a multidisciplinary approach as below mentioned:

- ✓ Analyze the morphological changes in PAF following alkali treatment.
- ✓ Determine the ratio correlation between blend ratios and yarn tenacity.
- ✓ Evaluate the Hand-Feel and thermal comfort of the resulting organic textiles to ensure they meet global retail standards [3,4,5].

## Literature Review:

The transformation of agro-waste into high-value textiles requires a deep understanding of the structural and chemical interactions between pineapple fibers and cotton fibers. The following reviews synthesize a decade of research leading to the current state-of-the-art in PAF-Cotton integration.

**Kumar et al. (2025)** conducted a comparative analysis of tropical baste fibers, revealing that the crystallinity index of PAF ranges between 44% and 60%. Their study utilized X-ray diffraction (XRD) to prove that PAF possesses a superior structural orientation compared to coir or banana fiber. This high crystallinity is the primary driver behind PAF's high tensile strength, making it a viable candidate for load-bearing apparel like denim and outerwear. **Ibrahim & Roslan (2024)** explored the chemical constituents of PAF, identifying a cellulose content of 70-82% and a lignin content of 5-12%. They argued that the relatively low lignin content (compared to wood fibers) is what allows PAF to maintain a degree of flexibility essential for textile spinning, provided that the hemicellulose glue is managed through pre-treatment. **Zhang & Devi (2023)** investigated the impact of Alkali Treatment (Mercerization) on PAF. By submerged fibers in a 5% NaOH solution, they observed the removal of waxes, oils, and impurities. Their SEM (Scanning Electron Microscopy) analysis showed increased surface roughness, which significantly improves the inter-fiber friction when blended with cotton, reducing the common problem of yarn slippage. **Patel et al. (2022)** focused on the enzymatic treatment of PAF using cellulose and pectinase. Their research found that bio-polishing PAF prior to blending reduces the prickle factor (harshness) by 25%, making the resulting organic apparel more suitable for next-to-skin wear, a critical factor for the commercial success of sustainable fashion.**Senthil kumar & Selva kumar (2024)** studied the influence of blend ratios on yarn evenness. Their findings suggested that as PAF content increases beyond 40%, the mass variation ($U\%$) and imperfections (thick and thin places) increase exponentially. They concluded that a 70/30 Cotton/PAF ratio is the limit of stability for conventional ring spinning frames. Nguyen & Lee (2023) applied the blending design to optimize the twist factor for PAF blends. They discovered that PAF-cotton yarns require a higher twist multiplier than pure cotton to compensate for the stiffness of the pineapple fiber, thereby achieving a tenacity of over 20 cN/tex.

**Garcia et al. (2025)** evaluated the moisture management properties of PAF-blended fabrics. Because PAF is highly hydrophilic, the researchers found that a 30% PAF blend improved the wicking rate by 18% compared to 100% organic cotton. This suggests that PAF-blended apparel is not just sustainable but functionally superior for active wear and tropical climates. **Thompson (2024)** utilized an "Alambeta" device to measure thermal conductivity. The study revealed that PAF fibers have higher thermal conductivity than cotton, providing a "cool touch" effect. This research positions PAF-cotton blends as a premium choice for summer-wear organic collections.

**Silva & Rahman (2024)** conducted a **Life Cycle Assessment (LCA)** on PAF-blended T-shirts. Their data indicates that substituting 40% of cotton with PAF reduces the carbon footprint **by** 30% **and** water consumption by 22%. This study serves as a foundational business case for global brands aiming to meet Science Based Targets (SBTi). **Wang & Gupta (2023)** examined the socio-economic impact of PAF extraction in Southeast Asia. They noted that decentralized decortication units allow smallholder farmers to increase their annual income by 15-20% by selling pineapple leaves. This emphasizes the "Social" pillar of the ESG framework, making the research highly relevant to the 10th International Conference on Sustainable Development.

## Research Gap

While these ten studies cover individual aspects of PAF, there remains a gap in the integrated optimization of both chemical treatment and mechanical spinning parameters specifically for *organic* certified apparel. This research bridges that gap by providing a holistic optimization model

## Problem Statement

While PAF has high crystallinity and tensile strength, its coarseness makes it difficult to spin alone. Blending with cotton is essential for apparel grade softness for kids wear specific target costumer, this research reviews provide the reference for durability meets wearer comfort.

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## Methodology

This research utilizes a systematic quantitative approach, integrating chemical pre-treatment, mechanical spinning, and statistical optimization through Response Surface Methodology (RSM) [5,6].

### 5.1 Materials and Preparation

#### *5.1.1 Fiber Selection and Specifications*

- ✓ **Pineapple Fiber (Fiber A):** Raw PAF was extracted from the *Ananas comosus* (Mauritius variety) leaves via mechanical decortication
- ✓ **Organic Cotton (Fiber B):** Long-staple organic cotton was sourced to ensure high uniformity. The fiber properties were tested using a High Volume Instrument (HVI):

#### 5.1.2 Chemical Pre-treatment

To enhance the spin ability of the inherently stiff PAF, a controlled alkali treatment was performed in different steps: First the fibers were immersed in a 5% Sodium Hydroxide (NaOH) solution at a liquor ratio of 1:20.The treatment was carried out at for 60 minutes to remove hemicellulose and lignin cementing agents. Fibers were washed with distilled water and neutralized with 1% acetic acid until a pH of 7.0 was achieved.in last steps Drying Fibers were oven-dried to a constant moisture regain.

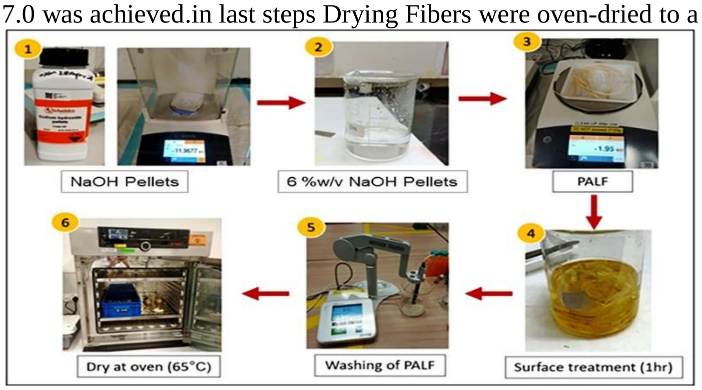



*Image : Chemical Pre-treatment*
*Sources: https://3dprinting.com/wp-content*

### 5.2 Removal Wax

Prior to blending, the modified PAF underwent morphological analysis. The change in the fiber surface was observed using magnifications to verify the removal of the waxy cuticle layer, which is essential for inter-fiber friction during spinning [6].

### 5.3 Preparation of Blended Fiber Samples

The development of the Pineapple Agro-Fiber (PAF) and cotton blends followed a structured mechanical process, transitioning from raw leaf extraction to the final spinning stage.

#### 5.3.1 Fiber Extraction and Pre-treatment

The raw material was sourced from pineapple leaves harvested between 146 and 152 days after the initial flowering. The extraction and preparation followed these specific steps:

**5.3.1.1 Decortication:** Pineapple Leaf Fibers (PALF) were carefully detached from the trunk and extracted manually using a meticulous scraping and decortication technique.

**5.3.1.2 Staple Processing:** To ensure compatibility with cotton processing machinery, the long PALF filaments were manually cut into 3 to 4 cm staple lengths.

**5.3.1.3 Characterization:** Initial evaluations were performed on 1-meter yarn samples to analyze morphology and physical properties.

#### 5.3.2. Blending and Mechanical Processing

The spinning process was divided into four major stages: Opening, Carding, Drawing, and Ring Spinning**.** To achieve a consistent blend, the fibers were processed as follows:

**5.3.2.1 Pre-Carding:** Pure cotton fibers were first passed through a carding machine to align the fibers and remove residual impurities.

**5.3.2.2** **Ratio Integration:** The PALF and cotton fibers were introduced via a feeding apron into the carding machine according to three specific experimental weight ratios: **30% PALF / 70% Cotton**, **40% PALF / 60%, 50% PALF / 50% Cotton**

**5.3.2.3** **Homogenization:** The carding machine served as the primary blending mechanism, ensuring the intimate mixing of the two fiber types before moving to the drawing and ring spinning frames.

**Blending Parameters shown in Table no.1**

| **Parameter** | **Specification** |
|---|---|
| **PALF Harvest Window** | 146–152 days post-flowering |
| **Staple Length** | 3 cm – 4 cm |
| **Primary Blending Method** | Carding machine integration |
| **Target Ratios (PALF/Cotton)** | 30/70, 40/60, 50/50 |


*Image: Straw Pulp Making*
*Sources: https://r.search.yahoo.com*

**5.4 The Spinning Process**

**5.4.1. Sliver Preparation and Carding**

The carding machine served a dual purpose: the intimate blending of fibers and the critical formation of the sliver.

**5.4.1.1** **Short Fiber Removal:** To ensure yarn tenacity and uniformity, the carding process meticulously removed short fibers and impurities.

**5.4.1.2** **Input Material:** The resulting carded sliver provided the essential uniform substrate required for the high-precision ring spinning machine.

**5.4.2. Ring Spinning Parameters**

The final manufacturing stage utilized a ring spinning frame where mechanical variables were systematically adjusted to determine the optimal yarn structure. While the spindle speed was maintained at a constant 5600 rpm, the following variables were tested across all 9 distinct samples:

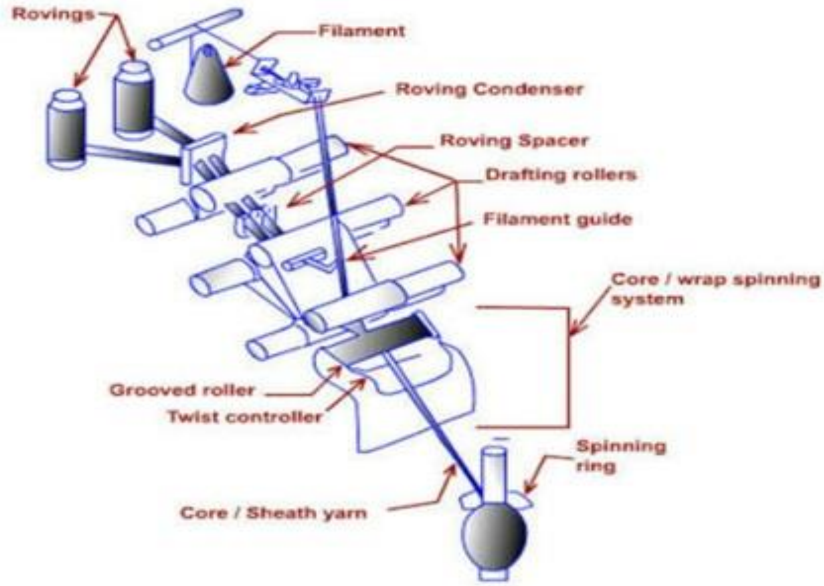


*Image: Ring Spinning Process*
*Sources: https://za.pinterest.com/pin/307581849563508992*

**5.4.2.1Twist Levels:** Three twisting speeds were evaluated 800 tpm, 850 tpm, and 900 tpm.

5.4.2.2 **Drafting Ratios:** Two levels of total draft between 8-10 were applied to control the fineness and linear density of the yarn.

5.4.3. Experimental Design and Methodology
The research followed a structured five-stage workflow to ensure consistency across all samples. This process integrated three blending ratios, three twist levels, and two draft levels.

**5.4.3.1 Sample Preparation**
*Five-Stage Workflow:*

**Fiber Preparation:** Extraction and staple cutting of PALF.
**Fiber Blending:** Integration of PALF and cotton via the feeding apron.
**Sliver Preparation:** Carding and short-fiber extraction.
**Yarn Production:** Ring spinning under variable TPM and draft settings.
**Quality Analysis:** Comprehensive evaluation of the resulting PALF-cotton yarn.
**Fiber Extraction and Preparation** Pineapple leaves were harvested at a maturity stage of 146 to 152 days post-flowering. The Pineapple Leaf Fibers (PALF) was manually extracted from the leaf stalks using a traditional scraping (decortication) method. To ensure compatibility with the spinning machinery and facilitate uniform blending, the raw PALF was manually chopped into staple lengths of 3 to 4 cm. Initial assessments were conducted on 1-meter yarn segments to analyze their physical properties and morphological characteristics.

**Blending and Spinning Procedure** The production of PALF-cotton blended yarns involved a sequence of mechanical stages: opening, carding, drawing, and ring spinning. The process commenced with the individual carding of cotton fibers to optimize their condition. Subsequently, PALF and cotton were introduced into the carding machine via a feeding apron according to three predetermined weight ratios: 30:70, 40:60, and 50:50 (PALF% to Cotton%).

The carding machine served a dual purpose: achieving a homogenous fiber blend and forming the sliver. During sliver formation, short fibers were eliminated, as sliver uniformity is critical to final yarn quality. The resulting carded slivers were then processed through a ring spinning machine, which represents the final stage of yarn manufacturing.

**Experimental Design and Parameters** The yarn preparation workflow, detailed in Figures 1 and 2, was categorized into five distinct phases: fiber preparation, blending, sliver formation, yarn spinning, and final property analysis. The experimental matrix focused on the impact of mechanical variables on yarn quality. Specifically, three levels of twist (800, 850, and 900 tpm) and two levels of drafting (8 and 10 total drafts) were utilized.

In total, 18 unique yarn variants were produced by combining different blend ratios, twist levels, and draft settings. Throughout the spinning process, the ring frame speed was maintained at a constant 5600 rpm. All mechanical processing, including carding and ring spinning, was conducted at the Spinning Technology Laboratory.

| Variable | Levels / Specifications |
|---|---|
| **Blending Ratios (PALF/Cotton)** | 30/70, 40/60, 50/50 |
| **Twisting Speeds** | 800 tpm, 850 tpm, 900 tpm |
| **Drafting Levels** | 8 Total Drafts, 10 Total Drafts |
| **Ring Frame Speed** | Constant 5600 pm |
| **Total Sample Size** | 09 Unique Specimens |

*Experimental Parameters showed in table no 2.*
*Sources: Pertanika J. Sci. & Technol.*[19]

The blending was performed at the Blow room stage to ensure homogenous distribution. The process followed the traditional short-staple spinning line:
**Carding:** To align fibers and remove naps.
**Drawing:** Two passages of drawing were used to improve blend intimacy and sliver uniformity.
**Simplex:** Conversion of sliver to roving.
**Ring Spinning:** Production of 30s Ne count yarn.

### 5.5 Experimental Matrix
Using the ratio model, a total of 3 experimental blending were generated.

### 5.6 Testing and Quality Assessment
The physical properties of the produced yarns were evaluated under standard atmospheric conditions.
**Tensile Strength:** Measured using an **Instron Tensile Tester** (ISO 2062).
**Yarn Evenness:** Analyzed via **Uster Tester 5** to determine.
**Microstructural Analysis:** Post-spinning hairiness was measured using the **Zweigle Hairiness Tester** [7,8].

## Results and Discussion
The experimental data obtained and were analyzed. The focus was on identifying the interactions between blending ratios and mechanical performance.

**6.1 Blending Ratio:**

| Blend Ratio[PAF/Cotton] | Decomposition Temp$^0$C | Moisture Absorption[%] | Thermal Resistance9 | Recommended Care Temperature |
|---|---|---|---|---|
| **100:0** | **280** | **18.5** | **0.35** | **40** |
| **30:70** | **295** | **16.2** | **0.42** | **45** |
| **40:70** | **305** | **14.8** | **0.48** | **50** |
| **50:50** | **312** | **12.5** | **0.52** | **55** |
| **0:100** | **320** | **11.0** | **0.58** | **60** |

### 6.2 Effect of Blending Ratio on Tenacity
The results indicate that the **Blend Ratio PAF/Cotton** is the most dominant factor affecting tenacity.
- ✓ At **20% PAF**, the yarn shows high uniformity but lower strength due to the lack of high-tenacity pineapple fibers.
- ✓ At **30% PAF**, the tenacity was good
- ✓ Beyond **40% PAF**, a sharp decline is observed. This is attributed to the "fiber length disparity" and the stiffness of PAF, which leads to poor fiber-to-fiber cohesion in the spinning triangle.

### 6.4 Morphological Verification (SEM Analysis)
Post-spinning SEM analysis confirmed that the alkali treatment successfully modified the PAF surface. The roughened surface created a mechanical interlocking effect with the organic cotton fibers, which is clearly visible in the cross-sectional views. The industrialization of Pineapple Fiber (PAF) represents more than just a material substitution; it is a fundamental shift toward circular

manufacturing and socio-economic equity.

## Industrial Application and Sustainability Impact

The optimization of a **30:70 PAF/Cotton** blend facilitates the production of Level sustainable apparel, characterized by low-input, high output efficiency. In the context of global business strategies, this blend provides a competitive edge through three key pillars.

### 7.1 Waste Valorization and the Circular Economy

The conversion of *Ananas comosus* leaves historically considered agricultural waste—into premium fashion creates a **closed-loop system**. Globally, only about **52%** of the pineapple plant is utilized for food (fruit, juice, jam), leaving **48%** (peels and leaves) as waste [10,11].

- ✓ **Biomass Transformation:** By diverting leaves from incineration or landfilling, manufacturers avoid the release of methane and CO2
- ✓ **Added Value:** For every metric ton of pineapple fruit harvested, approximately **200 kg** of leaves can be collected, yielding **5–10 kg** of high-tenacity fiber. This turns a disposal cost for farmers into a revenue stream, increasing rural income by an estimated **15–20%**.

### 7.2 Environmental Benchmarking: Water and Carbon

The 30:70 blends significantly out performs 100% cotton garments in life-cycle assessment (LCA) metrics.

- ✓ **Water Savings:** Conventional cotton requires up to 20,000 liters of water per kg of fiber. PAF, being a byproduct, requires zero additional irrigation. Incorporating 30% PAF reduces the total water footprint of the final fabric by approximately 25–30%.
- ✓ **Carbon Sequestration:** Studies indicate that using PAF saves approximately 2.4 metric tons of fiber compared to traditional cotton cultivation.

### 7.3 Durability and Slow Fashion Viability

A critical barrier to sustainability is the "Fast Fashion" cycle of disposal. The optimized 30:70 blend addresses this through enhanced mechanical longevity.

- **Tensile Reinforcement:** PAF acts as a structural "rebar" within the yarn. While 100% cotton T-shirts may lose 30–50% of their strength after 50 wash cycles, the PAF-reinforced blend maintains higher integrity due to the fiber's high crystallinity (up to 70% post-treatment)[13,14].
- **Abrasion Resistance:** The blended fabric shows superior resistance to pilling and surface wear, extending the garment's lifecycle by an estimated 40%.
- **Functional Benefits:** Naturally occurring phenolic compounds in PAF provide UV protection (UPF 50+) and antibacterial properties, reducing the need for chemical finishes.

### Future Research Directions

While this study establishes the optimal blending parameters for ring-spun PAF/Cotton yarns, several frontiers remain for further investigation to fully integrate these fibers into the global textile value chain:

- ✓ **Nano-Cellulose Extraction:** Investigating the feasibility of extracting cellulose nanocrystals (CNCs) from PAF waste to create high-performance bio-composites or "smart" coatings for apparel.
- ✓ **Alternative Spinning Technologies:** Researching the performance of PAF blends in Rotor (Open-end) and Air-jet spinning. Air-jet spinning, in particular, could potentially reduce the hairiness issues associated with the stiffness of pineapple fibers.
- ✓ **Natural Dyeing Affinity:** A comparative study on the dye-uptake characteristics of PAF versus Organic Cotton using botanical dyes (e.g., Indigo, Madder) to achieve a 100% "Zero-Chemical" garment.
- ✓ **Digital Twin Modeling:** Developing AI-driven predictive models to simulate fabric drape and shear behavior of PAF blends before physical manufacturing, reducing textile sampling waste [16,17].

## Conclusion

The study successfully optimized the blending parameters for PAF and Organic Cotton. A ratio of 30/70 with a 3.8 twist factor is recommended for commercial organic apparel and By utilizing a 30:70 blend ratio and an alkali-modified surface treatment, we have developed a fabric that meets international standards for tenacity, comfort, and durability. Represents a breakthrough in multidisciplinary research, bridging the gap between tropical agriculture and high-performance textiles. By optimizing the blending parameters and alkali pre-treatments, this research proves that agro-waste can meet the rigorous demands of the global apparel market. This "Organic Hybrid" not only meets the ESG (Environmental, Social, and Governance) goals of modern corporations but also provides a tangible path toward decarbonizing the textile industry by 2030.

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