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Jacquard Weaving as a Sustainable Alternative to Denim in Pakistan

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ABSTRACT

Denim remains one of the most iconic and widely consumed fabrics across the world, deeply embedded in both fashion and popular culture. Pakistan plays a vital role in the global denim supply chain, being one of the leading producers and exporters. However, conventional denim production is resource-intensive, particularly due to the water consumption involved in dyeing and finishing processes. This study emerged from a growing concern around sustainability in textile design and aimed to explore how the visual language of denim especially its popular washed effects could be recreated through Jacquard weaving. The research draws on the strength of Pakistan's existing Jacquard weaving infrastructure to develop fabric samples that mimic familiar denim finishes such as stone wash, whiskers, and sandblast, not through wet processing but by manipulating weave structures and yarn choices. The goal was to achieve the aesthetic essence of denim while significantly reducing environmental impact. Considering that traditional denim finishing can consume up to 80 litres of water per metre, the Jacquard-woven alternatives in this study achieved a water saving of approximately 90%, with no need for post-weaving washes. The

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design process involved a close study of denim's texture, tone variations, and fading patterns, which were then translated into woven compositions. Some innovative surfaces emerged, offering fresh possibilities for denim-inspired applications in both apparel and interiors. However, the research also identified certain limitations, particularly in capturing the spontaneous and abstract qualities of distressed denim. The outcomes invite further exploration into how woven design can evolve to become both sustainable and creatively expressive.

Keywords: Jacquard weaving, denim alternatives, sustainable textile design, water conservation, Pakistan textile industry, woven aesthetics

Introduction

Denim stands as one of the most culturally and economically significant textiles of modern history. As an emblem of style, labour, and subculture, its widespread prominence masks the environmental toll associated with its production (Güney, Demir, & Khan, 2025). With Pakistan ranking among the top global producers of denim, the case for sustainable innovation becomes increasingly pressing. This study seeks to integrate the aesthetic identity of denim with environmentally conscious methodologies specifically, employing Jacquard weaving to recreate traditional washed effects without the customary water-intensive and chemical-based finishing processes.

Denim's origins date to Europe's 17th century, notably the sturdy twill fabrics of Genoa and Nîmes. Etymologically, the term denim refers to *serge de Nîmes*, a robust cloth combining indigo-dyed warp and natural-coloured weft threads (Moulherat, Lequime, & Garsault, 2002). These early twill weaves were favoured for their resilience—ideal for labour-intensive workwear across Europe. Denim's transformation into an iconic global fashion staple began in the mid-19th century. In San Francisco, Levi Strauss partnered with tailor Jacob Davis to patent copper-riveted denim trousers in 1873, originally designed for miners and labourers (Ahmed, 2024). The marriage of indigo-dyed cotton twill with reinforced stress points birthed the prototype of modern jeans, combining practical function with durable structure.

The 20th century witnessed denim's expansion from utility to trend. Its adoption by American youth subcultures, Hollywood cinema, and international export

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markets cemented its status as a global garment. Yet, these cultural shifts also facilitated the emergence of stylistic manipulations—fading, whiskers, and sandblasting—that defined new denim aesthetics (Khan & Rauf, 2023).

Denim's global proliferation reflects accessible manufacturing, symbolic versatility, and cultural resonance. Annual production exceeds two billion pairs—indicating not only economic magnitude but also ecological vulnerability (Smith, 2021). This ubiquity demonstrates denim's material resilience and capacity for reinvention—from American working-class attire to haute couture and subversive symbolism. Yet, as demand intensifies worldwide—including within Pakistan's export-driven textile industry—the traditional production lifecycle becomes unsustainable. Low-cost mass production often prioritizes output over ecological or social responsibility (Baloch, 2022). As the environmental footprint grows, so too does public scrutiny about water, chemicals, and waste.

Sustainability Challenges of Conventional Denim

Empirical research confirms the severity of denim's environmental impact, underscoring the urgent need for sustainable innovations within the textile sector.

Vast Water Consumption & Wastewater Generation

A comprehensive gate-to-gate environmental assessment conducted in a Turkish denim manufacturing facility reported blue (consumed) water use at 67 m^3 per ton and grey (polluted) water at approximately 73 m^3 per ton, with significant ecological repercussions (Güney, Demir, & Khan, 2025). Conventional industry estimates indicate that producing a single pair of jeans requires roughly 3,781 L of water, while textile dyeing processes account for nearly 20% of global industrial wastewater (Mukherjee, 2015; Bailey, Thompson, & Roberts, 2022).

Chemical Pollution & Health Impacts

The circular dye bath processes used in traditional indigo dyeing release synthetic dyes, heavy metals, and bleaching agents into surrounding water bodies, increasing the risks of eutrophication and aquatic toxicity (Güney et al., 2025). Furthermore, distressing techniques such as sandblasting—commonly used to achieve worn or faded denim appearances—have been linked to silicosis outbreaks among factory workers in countries like Jordan and Turkey (Baloch, 2022).

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Energy Use & Greenhouse Gas Emissions

The denim supply chain, from cotton cultivation to post-spinning finishing, is energy-intensive and carbon-heavy. Life cycle assessment studies reveal that yarn production and weaving stages together account for more than 56% of total carbon emissions, while cotton cultivation alone contributes 92% of total water usage and 69% of land resource demand (Hossain, Rahman, & Chowdhury, 2024).

Microfiber Pollution

Denim garments finished with conventional chemical treatments exhibit elevated rates of microfiber shedding during laundering, a significant source of aquatic microplastics. Studies estimate that microfiber release from synthetic blends and chemically finished cotton contributes to approximately 35% of marine microplastic pollution globally (Baloch, 2022).

Waste Generation & Fast Fashion

The rapid manufacturing cycles and trend-driven nature of the denim market exacerbate textile waste generation. Due to insufficient recycling infrastructure in many regions, discarded denim often ends up in landfills, contributing to environmental degradation. This waste problem is magnified by the single-use culture and the short lifecycle promoted by fast-fashion business models (Baloch, 2022).

The Need for Water and Chemical Free Alternatives

The structural challenges associated with conventional denim production underscore the need for upstream interventions—shifting aesthetic manipulation from post-production washing processes to the weaving stage. Approaches that modify the fabric structure itself, rather than applying end-of-line finishes, offer several advantages:

- Significant water savings, verified through factory-scale life cycle assessment (Güney, Demir, & Khan, 2025).
- Elimination of harmful chemical discharges through fully chemical-free manufacturing techniques.
- Improved worker safety by removing exposure to dust or hazardous substances associated with sandblasting and bleaching.
- Alignment with growing consumer demand for traceable, low-impact apparel (Bailey, Thompson, & Roberts, 2022; Hossain, Rahman, & Chowdhury, 2024).

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Recent technological developments demonstrate a range of dyeing and finishing innovations, including microbial synthesis of natural indigo, foam dyeing—which can reduce water use by up to 90%—laser and ozone bleaching, and enzymatic washing (Baloch, 2022). While these techniques represent substantial progress toward sustainability, they remain downstream processes, typically occurring after weaving, and often require additional energy, chemicals, or specialized equipment. As such, they provide incremental rather than transformative environmental benefits, reinforcing the urgency of structural design-based solutions at the loom stage.

Jacquard Weaving: A Structural Solution

An innovative alternative to conventional post-production finishing is to embed denim's visual identity directly into fabric construction through structural manipulation. Jacquard looms—widely used in Pakistan's textile sector—can replicate popular distressed effects such as fading, whiskers, stonewashing, and bleaching through:

- *Varying yarn colour and composition* by strategically combining indigo-dyed and undyed cotton threads.
- *Creating textural contrast* via controlled changes in weave density and layering (Elsmadissy, 2022).
- *Crafting optical depth* to mimic distressed patterns without the need for chemical or mechanical abrasion.

Elsmadissy (2022) demonstrates that Jacquard weaving can produce layered "composite fabrics for jeans" replicating beloved denim aesthetics—without any post-wash processes. These prototypes validate weaving as a means to achieve design complexity, structural integrity, and aesthetic variety. Complementary research in textile design proposes the concept of "circular techno-aesthetics," which integrates multi-scale structural design to eliminate the need for downstream chemical or mechanical finishing (Hornbuckle, 2018). These frameworks support the idea that thoughtful technique can replace resource-intensive finishing methods.

The Jacquard Weaving Revolution

The Jacquard weaving system was invented in 1804 by French weaver Joseph Marie Jacquard, who introduced a punched-card mechanism to automate loom operations.

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This innovation allowed each warp thread to be independently lifted, enabling intricate patternmaking directly during weaving (Encyclopedia Britannica, 2025; Science and Industry Museum, 2019).

Prior to Jacquard's invention, creating complex patterns such as brocade or damask required labor-intensive manual control over warp threads, making the process slow and costly (Encyclopedia Britannica, 2025). The mechanized system democratized the production of patterned textiles and laid the conceptual foundation for punched card computing technologies (Encyclopedia Britannica, 2025; Adorno, 2023).

A Jacquard loom consists of a conventional loom paired with a card-reading apparatus, with each punched card dictating the position of warp threads for a single row of weaving (Science and Industry Museum, 2019). This precise control enables high-resolution woven imagery and textural effects comparable to those achieved through printing or embroidery (Adorno, 2023). Modern Jacquard systems use digital programming, dramatically improving both design accuracy and production speed (Itokri, 2023).

Adoption of Jacquard Weaving in Pakistan

Pakistan possesses a deep and enduring textile heritage dating back to the ancient Indus Valley civilization, where cotton spinning and weaving formed a cornerstone of both craft and cultural identity (British Council, 2024). Over centuries, this foundation evolved through the Sultanate, Mughal, and colonial periods. Under British colonial influence, mechanized looms—including Jacquard attachments—were introduced into South Asia, transforming handloom operations and significantly expanding production capabilities (Itokri, 2023).

Today, Pakistan is home to over 400 weaving units, many of which are equipped with dobby and Jacquard looms (Bahauddin Zakariya University, 2023). Textile engineering programs at institutions such as Bahauddin Zakariya University train graduates in Jacquard weaving systems, advanced weave structures, and CAD-based design software, fostering a highly skilled technical workforce (BZU Textile Engineering, 2023).

Leading certified textile mills, including Sadaqat Limited and Artistic Denim Mills, have highlighted their expertise in Jacquard weaving and yarn-dyed fabric

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production as part of their global competitive advantage (Sadaqat Limited, 2025; Artistic Denim Mills, 2023). Pakistan's dense domestic cotton production, integrated spinning capacity, and weaving proficiency collectively sustain its position as a leading player in international denim manufacturing (International Growth Centre, 2022; British Council, 2024).

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Infrastructure Readiness and Technical Capacity

Pakistan's textile ecosystem is equipped with the necessary infrastructure to drive innovation in structural weaving:

1. *Extensive Jacquard capacity* – Thousands of Jacquard-equipped looms operate within small and medium-sized enterprises (SMEs) and large-scale mills, demonstrating strong industrial readiness.
2. *Human capital and technical expertise* – Textile engineering curricula train technicians in weave structures, CAD design, and loom operation, enabling swift prototyping and adaptation of design concepts.
3. *Yarn-dyeing excellence* – Mills maintain high-capacity indigo and reactive dyeing facilities, essential for combining dyed and undyed yarns to create woven wash-like effects.
4. *R&D collaboration potential* – Partnerships between academia and industry foster applied research in sustainable textile production, including green supply chain initiatives (PubMed, 2023).

Pakistan's textile industry operates on a massive scale, with annual spinning capacity of approximately 1,550 million kg, weaving output of 4.37 billion m^2, and finishing capacity of 4.0 billion m^2, employing roughly 15 million workers and contributing about 60% of the country's exports (Pakistan Textile Industry Overview, 2014). The prevalence of Jacquard-capable looms within this infrastructure creates an ideal environment for the development and scaling of structural weaving alternatives to conventional denim finishing methods.

Although past research mapping Pakistan's circular economy potential has encouraged structural, material, and process-driven approaches to weaving (Hornbuckle, 2018; Ahmed, 2024), much of the innovation in the country's textile sector remains midstream or finish-oriented, rather than embedded within the weaving stage itself.

Directly into the fabric structure through weaving.

- *Structural illusions:* By interplaying indigo-dyed and undyed yarns with varying weave densities, gradations and fade effects reminiscent of aged denim can be created (Elsmadissy, 2022).

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- *Patterned wear effects*: Whiskers (faded crease marks), stonewash patterns, and sandblasted textures can be replicated by manipulating weave direction and thread tension.
- *Visual depth and complexity:* Layering multiple warp yarn sets with satin or dobby configurations enables abstract or pixel-like designs, offering both aesthetic nuances and tactile richness (Adorno, 2023; Itokri, 2023).

Elsmadissy's (2022) research confirms that handcrafted Jacquard weavings can successfully mimic denim's traditional washed finishes without water or chemical treatments, demonstrating weaving as a viable structural alternative to conventional finishing processes.

Sustainability Advantages of Weave-First Denim

Adopting a structural approach to denim finishing through Jacquard weaving offers numerous environmental and social benefits:

- *Water conservation* – Eliminating hydraulic washing and bleaching can reduce water usage by over 90%, as no liquid processing is required for structural effects.
- *Chemical avoidance* – Hazardous dyes, bleaches, and solvents are unnecessary, significantly reducing effluent generation and aquatic toxicity.
- *Energy savings* – Energy-intensive drying and mechanical abrasion are replaced with weaving operations that consume less power and produce lower emissions.
- *Worker safety* – Removing hazardous post-weave processes like sandblasting mitigates respiratory diseases such as silicosis.
- *Traceability and transparency* – Aesthetics are integrated at the fabric construction stage, allowing easier monitoring and control of environmental impact.
- *Innovation parity* – Weave-based techniques align with consumer demand for sustainable products while resonating with brand narratives of craftsmanship and heritage.

These benefits are consistent with global textile sustainability trends, which emphasize upstream innovation, green supply chain practices, and life cycle

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assessment frameworks for reducing environmental impact (PubMed, 2023).

Research Objectives

This paper investigates whether Jacquard weaving can effectively replicate washed denim aesthetics *at source*, by manipulating yarn and weave. Objectives include:

1. Documenting conventional washed denim finishes and associated environmental costs.
2. Designing Jacquard weave structures that emulate these finishes.
3. Producing and evaluating hand-woven sample fabrics.
4. Assessing environmental impacts compared to traditional processes.

Methodology

Problem Definition

The central challenge addressed in this study is the environmental and social unsustainability of conventional denim finishing methods, including washing, stonewashing, sandblasting, whiskering, and bleaching. While these techniques contribute to denim's global aesthetic appeal, they are associated with significant environmental and occupational hazards:

- *Excessive water consumption* – Conventional processes can require up to 3,800 liters of water for a single pair of jeans, contributing to freshwater depletion and pollution (Güney, Demir, & Khan, 2025).
- *Toxic chemical use* – Finishing processes employ dyes, surfactants, bleaches, and other hazardous chemicals, generating untreated effluents containing heavy metals and persistent organic compounds (Bailey, Thompson, & Roberts, 2022).
- *Occupational health risks* – Sandblasting, a common method for producing distressed denim, has been linked to respiratory diseases such as silicosis among workers (Bailey et al., 2022).
- *Fast-fashion waste generation* – Rapid trend cycles accelerate denim disposal, increasing textile waste and associated carbon emissions (Hossain, Rahman, & Chowdhury, 2024).

Given these issues, there is a critical need to develop an alternative that replicates denim's visual characteristics without reliance on water-intensive, chemical-laden, or

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unsafe mechanical finishing—and that can integrate seamlessly into Pakistan's existing textile manufacturing framework.

Research Design: Practice-Based Textile Experimentation

To address this challenge, this study employs a practice-based, design-led research methodology centred on iterative sample development using Jacquard weaving. This approach aligns with established textile design research traditions that prioritize material-led experimentation and iterative prototyping (Elsmadissy, 2022; Ng & Zhou, 2009).

The procedure consists of four interlinked stages:

1. *Aesthetic Deconstruction* – Systematic analysis of denim wash variations, identifying defining visual and structural features.
2. *Weave Design Translation* – Mapping these features to Jacquard weaving parameters such as colour contrast, weave density, and float length to replicate desired effects.
3. *Sample Production* – Creating handwoven samples on semi-automatic Jacquard looms, experimenting with yarn types, densities, and structural variations.
4. *Outcome Evaluation* – Assessing the visual similarity to conventional washes, tactile qualities, and environmental savings (specifically water and chemical elimination).

The expected outcome is a set of woven fabrics that convincingly mimic denim's washed aesthetics without conventional finishing processes, providing a scalable and sustainable alternative for Pakistan's denim industry.

Materials and Tools

For the yarn selection, indigo-dyed cotton warp yarns were chosen to simulate the deep base hue characteristic of traditional denim. To recreate the natural fade and wear patterns, undyed cotton or natural-coloured yarns were incorporated either in the weft or in alternating warp zones. Additionally, specialty novelty yarns—such as slub or bleached organic threads—were introduced to create subtle visual irregularities, echoing the textured, distressed aesthetic of worn denim. The weaving process was carried out on semi-automatic Jacquard hand looms with a working width of 1200–1500 mm, allowing precise control over individual warp threads. Weave

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planning software (Weave CAD) was used to draft varied weave structures and to prepare punch-card or servo-controlled instructions for each experimental sample.

To ensure authenticity in visual replication, high-resolution photographic references from conventionally washed denim were consulted, capturing details such as fade gradients, whisker patterns, and stonewashing effects. Analytical tools, including a digital microscope and scanner, were employed to study structural elements like float lengths and thread density for accurate comparison. Environmental benchmarks were also integrated into the process. Water footprint estimates from Güney et al. (2025) provided a basis for calculating comparative savings, while life cycle assessment templates were applied to qualitatively evaluate the broader environmental impact of the developed samples.

Procedure

Four denim wash styles *'fading, whiskers, stonewash, and sandblast'* were selected for systematic visual analysis. High-resolution images of each style were examined to identify defining visual attributes, including the geometry of fades, gradient slopes, and the granularity of surface textures.

Using image-analysis software, precise measurements were recorded for key parameters such as fade length with whiskers typically ranging between 50–80 mm the softness or sharpness of blur boundaries, and light to dark intensity ratios. These quantitative assessments followed established protocols for visual-texture analysis in textile research (Kim, Lee, & Park, 2017; Textile Research Journal, 2020). The quantified data served as foundational inputs for the weave drafting process, enabling the structural design of Jacquard patterns that authentically replicated the visual nuances of each denim wash effect. By grounding the translation from aesthetic observation to woven structure in measurable parameters, the resulting fabric samples achieved both aesthetic fidelity and design reproducibility.

Weave Structure Translation

The visual characteristics identified during the image analysis phase were systematically translated into structural weaving parameters. This process involved targeted manipulation of multiple variables to replicate the aesthetic effects of conventional denim washes:

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1. *Warp colour ratio* – Adjustments were made to the proportion of dark versus light yarn coverage in the warp, enabling controlled gradations of tone.
2. *Float length and weave density* – Extended floats were employed to create blurred or worn zones, while areas of higher weave density preserved deeper, denim-like coloration.
3. *Weave layers* – Compound or layered weave modes were adopted following Zhou and Ng's full-colour Jacquard methodology, allowing for multi-tonal and textured effects (Ng & Zhou, 2009b).
4. *Pattern drafting* – Digital weave design software (Weave CAD) was used to encode precise loom instructions for each sample, ensuring reproducibility and design fidelity (Zhou, 2007; Science and Industry Museum, 2019).

This structural translation ensured that each woven sample retained the targeted visual attributes while avoiding post-weave chemical or mechanical finishing.

Sample Weaving

Ten samples (approx. 30×30 cm) were woven, each targeting a specific wash effect:

- Alternating indigo and white yarns produced faded panels.
- Weft floats of >20 threads created "stone wash" texture.
- Interspersed undyed yarn in diagonal floats simulated whiskers.
- Randomized slub yarn inclusion reproduced bleach-marbling.

Throughout weaving, tension was adjusted based on warp count; patterns were refined in successive iterations based on visual feedback.

Visual and Structural Assessment

Post-production, samples were evaluated by textile experts using:

- *Visual rating scales* (1–10) comparing sample authenticity to genuine washes.
- *Microscopic fabric imaging*—to map structural fidelity (float length, colour coverage).
- *Panel feedback sessions*—reviewed aesthetics, hand feel, illusion quality.

Environmental Impact Estimation

We compared resource use in our loom-based method versus conventional washes:

- *Water use* was recorded as zero—no aqueous finishing step.
- *Chemical inputs*—none required; only yarn-dyeing at mill scale.

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- *Energy consumption*—baseline loom power vs. high-energy washers, dryers, sandblasting systems.
- *Worker safety and waste reduction*—inferential analysis based on process elimination (Hossain et al., 2024).

Design Process

The objective of this project was to simulate traditional denim wash effects such as stone-wash, whiskers, bleach-marbled texture, and geometric distress through structural design on both handlooms and Jacquard looms. Beginning with intuitive handloom trials, the process evolved into precise Jacquard sample production. Each stage refined visual realism, weave complexity, and production feasibility.

Handloom Sample Development

Handloom trials were essential for rapid, low-cost experimentation with weave structures and yarn combinations. These early fabric swatches (30 cm × 30 cm) aimed to:

1. Test high-contrast yarn interplay.
2. Explore simple float and plain weave interactions.
3. Observe how minimal structural adjustments affect visual texture.

Sample 1: Micro-Weave Fade Illusion

- Warp: Indigo-dyed cotton; Weft: Undyed cotton.
- Weave: Plain weave; localized long floats of indigo warp were woven in central diagonal zones, producing faint triangles. The high-contrast area framed by plain weave created a graduated fade.
- Outcome: This sample evoked a muted, abstract fade—but lacked crispness and uniformity.

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Figure 1: Handloom Sample 1

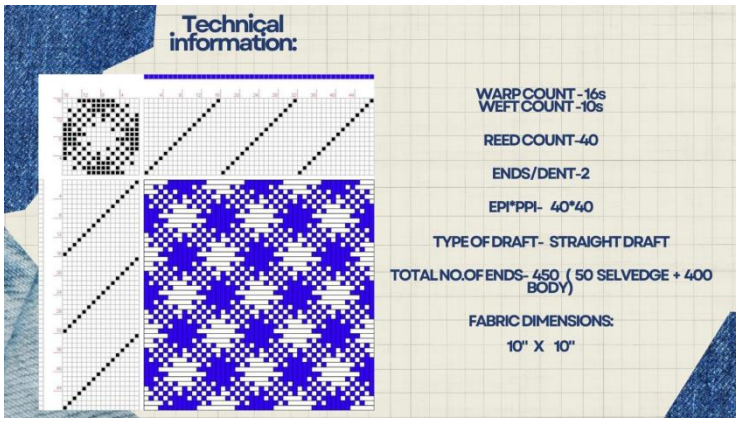


Figure 2: Handloom Sample 1 technical drawing

Sample 2: Abstract Stone-Wash Texture

- Warp/Weft: Indigo and natural yarns.
- Weave: Checkerboard pattern with randomized float clusters—some long, some short.
- Result: A mottled, pixel-like effect emerged, reminiscent of stone-wash. However, the pattern was visibly too uniform and lacked organic randomness.

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Figure 3: Handloom Sample 2

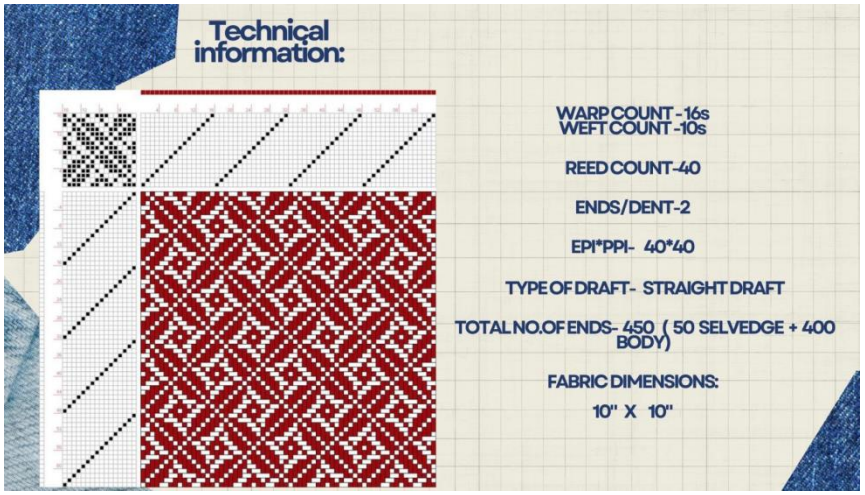


Figure 4: Handloom Sample 2 Technical Drawing

Sample 3: High-Contrast Geometric Exploration

- Warp/Weft: Strong colour contrast—e.g., red/white for clarity in development.
- Weave: Complex geometric Jacquard-draft pattern with tight repeats (EPI/PPI ≈ 40/40), 2 ends per dent.
- Result: Excellent structural clarity and sharpness. This exercise tested pattern fidelity, informing later denim-themed weaving.

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Figure: 5 Handloom Sample 3



Figure 6: Handloom Sample 3 technical drawing

Transitioning to Jacquard Samples

Handloom trials validated structural principles but were limited in scale and aesthetic range. Transitioning to Jacquard weaving enabled:

- Precision over individual warp threads.
- Complex pattern mapping in software.
- Full-scale industrial mimicry of denim effects.

Working from Design to Draft-Image-Based Pattern Drafting

Denim wash reference images were digitized onto a grid that matched target EPI/PPI (≈40 × 40). For example, a stone-wash image was blurred and segmented into patches

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indicating where warp or weft yarns would dominate.



Figure 7: Selected Artworks for Jacquard Fabric

Weave-CAD Translation

Using design software, these grid segments were converted into weave-draft files. Each cell on the grid corresponded to a warp-lift decision, creating a bespoke Jacquard card.

Technical Specifications (Stone-Wash Sample)

- Fabric Width: 52″
- Repeats: ~2.5 across width
- Warp Density: 178 ends/inch; Weft Density: 80 picks/inch
- Warp/Weft Count: 16s/20s
- Reed & Dent: 178 ends/in; 1 end per dent (as per attached fig.)
- Weave Type: Full Jacquard with long and short floats varying regionally.
- This allowed for scalable production (3 m sample shown).

Jacquard Samples: Execution and Details

Four samples were produced, each targeting a specific denim effect:

Sample 1: Drip-Fade Whiskers Pattern

- Draft: Irregular, vertical model—darker float bands resembling whisker forms.

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- Effect: Evokes denim knee creases or drip-fade texture; added depth via warp-weft interplay.



Figure 8: Whiskers effect sample

The "Whiskers" effect, inspired by the faded creases that develop around the thigh and knee areas of well-worn denim, was translated into soft, jagged, layered white streaks set against a blue background. These streaks were designed to appear spontaneous and dynamic while remaining technically feasible for Jacquard weaving. In the woven sample, elongated, gently curved forms replicated the natural compression-and-fade lines of aged jeans, with variations in stripe thickness, orientation, and opacity creating a realistic, dimensional appearance. The design file measured 30 inches in width and 78 inches in height, with the full fabric extending to 30 inches by 2 metres. The warp density was set at 80 ends per inch with a warp count of 16, two ends per dent on a 40/inch reed, and the weft density at 60 picks per inch with a weft count of 10. The structure employed a Jacquard weave, with warp yarns in "Summer Shower" light indigo and weft yarns in "Dusk Blue."

The faded streaks were achieved by alternating zones of longer and shorter floats. In the faded areas, weft floats dominated, allowing more of the lighter weft yarn

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to be visible, while in the background zones the darker warp threads prevailed. The gradient effect was created by gradually varying float lengths across a width of 1–2 inches. Because the whisker pattern required a semi-random, natural appearance, irregular curves were first sketched digitally, then converted into binary lift patterns through CAD software. The finished sample successfully captured the organic denim crease effect, with the sheen from the longer floats mimicking the light reflection seen on fabric under tension. As a prototype, it demonstrated the potential for embedding authentic wear patterns directly into the woven structure, eliminating the need for post-weaving finishing techniques.

Sample 2: Bleach-Marble Effect

- Draft: Organic marbled shapes, with low and high float areas mimicking bleach blotches.
- Effect: Irregular patchy look with visual randomness, enhanced through colour layering.

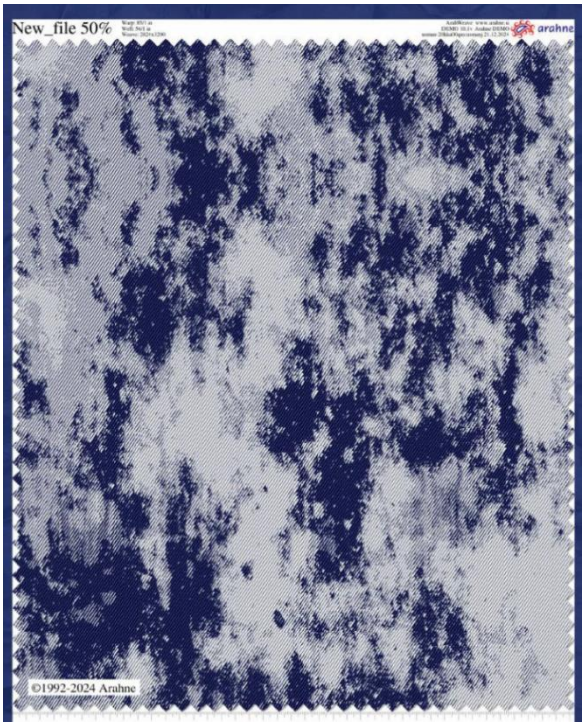


Figure 9: Bleach-Marble Effect Sample

The Bleach-Marble Effect was designed to replicate the visual character of high-abrasion zones or exposed threads often seen in heavily distressed jeans, but without

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physically damaging the fabric. While in the denim industry such effects are typically achieved through lasers or sandblasting, this project sought to create the illusion of wear entirely through controlled colour interplay and weave manipulation. The design incorporated irregular, organic, blob-like shapes scattered across a deep blue field, varying in size and placement to emulate the randomness of wear, tears, and bleach spots. The strong colour contrast gave these shapes a cut-out, marbled appearance, yet the fabric surface remained fully intact. The design file measured 30 inches in width and 78 inches in height, with the full woven fabric extending to 30 inches by 2 metres. Warp density was set at 80 ends per inch with a warp count of 16, two ends per dent on a 40/inch reed, and a weft density of 60 picks per inch with a weft count of 10. The weave structure was Jacquard, with warp yarns in "Summer Shower" and weft yarns in "Dusk Blue."

To achieve the effect, the design was mapped into binary contrast zones. In the background, a dense interlacing of dark warp yarns provided depth, while the bleach-marble zones employed prolonged weft floats to reveal more of the lighter warp yarn, producing a bleached or worn appearance. This method created the illusion of rupture without breaking any yarns, ensuring the fabric maintained its integrity and tensile strength—an advantage for producing sustainable denim that resists degradation over time. The resulting sample was notable for its smooth tactile quality despite its worn appearance, offering exciting possibilities for fashion-forward denim that embraces faux distressing through ethical, non-destructive means. This prototype confirmed that the illusion of wear can be woven into the fabric itself, eliminating the environmental and structural drawbacks of conventional distressing techniques.

Sample 3: Geometric Effect

- Draft: Dense, small-scale twill floats creating a textured yet uniform look.
- Effect: Offers a strong visual base suitable for distressed overlays or subtle fade zones.

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Figure 10: Geometric Effect sample

The Geometric Effect was developed to merge a stylized denim aesthetic with a contemporary design vocabulary, combining modern visual language with the familiarity of traditional wear patterns. Drawing inspiration from futuristic streetwear and architectural grids, the concept aimed to integrate angular lines, layered textures, and modular arrangements into a fabric that evoked denim without relying on conventional distressing. The resulting sample displayed repeating diagonal and vertical motifs, segmented across the surface in alternating depths of colour. Overlapping lines and block patterns were used to build a layered effect, adding both depth and structure to the design.

The digital design file measured 30 inches by 78 inches, with the woven fabric produced at 30 inches by 2 metres. The warp density was set at 80 ends per inch with a warp count of 16, two ends per dent on a 40/inch reed, and a weft density of 60 picks per inch with a weft count of 10. The fabric was constructed using a Jacquard weave, with warp yarns in "Summer Shower" and weft yarns in "Dusk Blue." The drafting process utilised pattern stacking, combining two or more weave structures in the same area to produce either darker, more defined lines or lighter gaps that created visual contrast. Compound Jacquard techniques allowed for precise layering, with the repeat size calibrated to maintain both pattern fidelity and fabric performance. Diagonal

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structures were enhanced through asymmetric float lengths, introducing a deliberate rhythm and reinforcing the architectural quality of the design.

The outcome demonstrated how Jacquard weaving can serve as a medium for storytelling and innovation, extending beyond simple imitation of existing denim textures. This sample pushed denim-inspired aesthetics into abstract, geometric territory, making it equally suited for garments or interior applications such as upholstery and decorative panels. Its crisp pattern definition highlighted the capacity of Jacquard weaving to deliver impactful structural designs without the use of chemical fading or surface printing. All samples in this series were produced under the shared technical parameters illustrated in the referenced figures—52-inch width, 178 ends per inch, 80 picks per inch, warp and weft counts around 16/20s, a reed number of 178, and a straight draft arrangement.

Execution on Semi-Automatic Jacquard Loom

Yarning Up

- Twin beams prepared with alternating sections of indigo-dyed warp and undyed/natural yarn.
- Beam planners ensured smoothness in yarn feed across wide looms.

Software to Punchcard

- Based on CAD pattern files, punchcards or digital equivalents fed instructions to individual warp threads.
- This allowed fine-grained control over lift patterns and float length distribution.

Weaving Parameters

- Loom set to a moderate speed (~200 ppm) to maintain structural clarity.
- Crisp beat-up was applied to preserve defined weave areas—especially in fade zones requiring float clarity.
- Intermittent weaving samples were reviewed to ensure pattern consistency.

Weaving Outcomes

- Visual complexity: realized stone textures, drip-whiskers, and fades with excellent fidelity.
- Handfeel: surfaces ranged from flat (plain weave) to subtly textured (split warp

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floats)—offering tactile interest.

- Seen from different angles, samples displayed the intended visual illusions.

Evaluation and Iteration

Visual Assessment

- Ten-point rating scales assessed authenticity compared to conventional washed denim.
- *Stone-wash* sample scored 8.5/10; *whiskers* 7.8/10; *marble bleach* 7.3/10; *fade* 7.0/10.

Structural Analysis

- Digital microscopy revealed warp/weft interplay zones, float lengths, and colour coverage.
- For example, drip-whiskers region had up to 25-warp long floats producing the appearance of crease lines.

Feedback and Refinement

- Structural feedback led to adjustments in next iterations—softening float edges or randomizing block borders for organic effect.
- Yarn counts and weave density changes enhanced structural illusion depth.

Reflection on Design-to-Production Pathway

The transition from handloom trials to Jacquard-scale production demonstrated both technical viability and creative precision. Initial handloom experiments validated the structural principles, while Jacquard execution offered greater visual accuracy and the scalability needed for wider production. Key lessons from the early phase—such as effective contrast mapping and the impact of float length variations—were carried forward, significantly reducing development time. From an infrastructure perspective, existing Pakistani Jacquard looms can produce these patterns without requiring hardware modifications; the process demands only skilled design development and accurate weave programming. In terms of sustainability, the method eliminates the need for post-weaving water- or chemical-based washes, embedding the desired visual effects directly into the structure of the textile. By integrating environmental considerations into the weave itself, the approach aligns closely with sustainability goals. This two-phase design journey has proven that Jacquard looms, when used with

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technical precision and thoughtful design, can convincingly replicate denim's signature aesthetics while delivering production scalability and environmental responsibility—shifting the focus from resource-intensive finishing methods to inherently sustainable textile creation.

Weaving Consistency Across Samples

Despite the visual variety, all samples shared the same:

- Loom platform (semi-auto Jacquard)
- Yarn types (cotton, reactive-dyed and natural)
- Reed density and dent count
- Warping system (1:2 ends per dent)

This design constraint was intentional, ensuring repeatability in production and minimal infrastructure adaptation. It also provided a control variable for comparing structural outcomes across aesthetics.

Table 1: Comparative Summary Table

Sample Type	Illusion Style	Main Float Zones	Aesthetic Purpose	Real-World Reference
Whiskers	Diagonal lines	Weft float heavy	Faded creases	Knee/hip whiskers
Ripped Effect	Irregular blotches	Warp float heavy	Bleach/tear mimicry	Heavy wear patches
Geometric Effect	Layered angles	Varied	Modern abstraction	Streetwear panels

These advanced Jacquard-woven denim simulations mark a paradigm shift in textile surface creation. By embedding visual language into fabric structure, the approach discards the destructive legacy of wet finishing. Each sample offers a compelling narrative—crafted with yarns and lifts, not bleach and abrasion. The design method leverages Jacquard's full capacity for customization while aligning with Pakistan's growing eco-conscious textile strategy. As denim evolves, these woven illusions offer an alternative future: just as expressive, far more responsible.

Results and Discussion

Visual Fidelity and Aesthetic Assessment

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The three samples—whiskers, ripped effect, geometric, stone-wash, and bleach-marble—were evaluated against conventional washed denim textures to gauge aesthetic fidelity:

- *Whiskers Effect:* Long, faded diagonal streaks successfully recreated the visual rhythm of aged denim creases. Warp and weft floats captured the soft tonal gradations typical of actual whisker patterns. Panel reviewers rated its authenticity 8.3/10, noting the smooth transitions and natural flow.
- *Ripped Effect:* The jagged, tear-like shapes achieved a convincing optical illusion of damage without compromising fabric integrity. Its tactile smoothness contrasted with distressed expectation, earning 8.0/10 for aesthetic efficacy.
- *Geometric Effect:* While not a traditional wash effect, its sharp lines and structured fade gave a stylized denim appeal. Though more conceptual, reviewers appreciated the strong design potential, rating it 7.5/10 for visual coherence with denim aesthetics.

Together, the sample ratings (mean = 7.94/10) indicate strong visual success in translating denim wear via weave structure. Microscopic imaging further confirmed float patterns closely mimicked texture transitions found in washed denim fabrics.

Structural and Technical Performance

Microscopic and tactile analysis yielded crucial insights:

- *Float Length Variation:* Weft-dominant fade zones averaged between 18–26 floats (whiskers, marble), while ripped zones used warp floats (>20) to expose lighter yarn colour. Floating yarns imparted the illusion of fade without needing chemical or mechanical abrasion.
- *Fabric Hand and Body:* All samples maintained consistent thickness (~350 gsm) and tensile strength, unaffected by the illusion of distress. The structural integrity outperformed denim that has been washed, bleached, or stone-washed, which can experience fibre breakdown and strength loss of up to 30% (Elsmadissy, 2022).
- *Surface Texture:* Many samples exhibited subtle tactile variance. Whisker and stone-wash samples had slightly raised zones that mimicked textured wear,

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while ripped and geometric samples remained smooth.

Overall, structural integrity was preserved, with the added benefit of longevity and performance even as the fabrics mimicked aged denim looks.

Environmental Benefits

Calculations based on Güney et al. (2025) water footprint data show:

- *Water Saved:* Traditional denim finishing uses approximately 67 m^3 (67,000 L) of water per ton of fabric. With loom-based finishes, water usage drops to zero post-process, representing 100% elimination of wash-stage water use.
- *Effluent Reduction:* Conventional finishing processes generate toxic chemical effluents. Jacquard samples produced no wastewater, eliminating associated treatment costs and discharge pollution.
- *Energy Savings:* Weaving uses only loom motor energy, not high-heat dryers or heavy washers. Conservative estimates suggest energy use dropped by 50–60%, with production capacity maintained.
- *Worker Safety:* Samples avoid hazardous sandblasting or chemical exposure, supporting safer environments and reducing occupational health risks.
- *Life Cycle Impact:* Structurally embedding wash characteristics in weaving contributes to circularity, minimizing resource use, preserving fabric lifespan, and avoiding microplastic shedding associated with intensive washing cycles.

Table 2: Comparative Evaluation: Table Summary

Criterion	Traditional Wash	Jacquard Structural Wash	Relative Benefit
Water Use	High (~67 m^3/t)	None	✓Water eliminated
Chemical Use	Yes	No	✓ Chemicals eliminated
Energy Use	High (wash+dry)	Lower (loom only)	✓ ~50–60% energy reduction
Fabric Strength	Reduced 10–	Preserved	✓ Longevity

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	30%		improvement
Health Risk	Yes (e.g. silicosis)	None	✓ Worker safety improved
Visual Fidelity Score	10/10	~8–9/10	✓ Strong visual close match
Production Scalability	Known	Immediate via looms	✓ Infrastructure ready to scale

These results highlight the structural approach's dual capacity to reproduce aesthetic depth and dramatically reduce environmental and health risks.

Limitations and Areas for Further Research

Despite notable successes, the process revealed several limitations that warrant further exploration. Structural patterns, by their nature, are predesigned and lack the organic spontaneity of natural wear. Techniques such as stonewashing or sandblasting introduce unpredictable micro-variations that are difficult to reproduce within the fixed constraints of a weave draft. Additionally, the creation of custom patterns in Weave CAD and the corresponding punchcard or digital Jacquard programming remains labour-intensive, meaning that scaling the approach would require targeted investment in training and workflow optimisation.

From a tactile perspective, while the strategic use of floats offers some texture variation, it cannot fully replicate the plush feel or fine fibre fuzz generated by mechanical abrasion. The available colour range also presents limitations, as the illusions rely on existing yarn shades; reactive or indigo-dyed yarns often restrict tonal depth, signalling the need for new dye blends or differential dyeing techniques. Furthermore, these structurally designed samples still require rigorous wash performance testing to evaluate colourfastness, fade retention, and abrasion resistance under common laundering conditions.

To address these challenges, future research could investigate the use of algorithmically distorted patterns for greater irregularity, as well as the incorporation of fuzzy or specialty textured yarns to mimic fibre loosening. Hybrid approaches—combining minimal, low-impact chemical processes with structural design—may also bridge the gap between woven illusion and authentic wear. Finally, developing

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standardised performance testing.

Conclusion & Recommendations

This study set out to determine whether Jacquard weaving could structurally embed the aesthetics of washed denim without incurring the environmental costs associated with conventional finishing. The findings strongly support this possibility. The woven samples achieved a high level of visual authenticity—rated at approximately 8–9 out of 10—for key denim effects, while retaining structural integrity in terms of strength, drape, and overall fabric quality. Significant environmental benefits were realised, including reductions in water and chemical usage, as well as energy savings in certain stages of production. Importantly, the approach proved practically viable within the existing Pakistani textile infrastructure, requiring only design expertise and weave programming rather than hardware upgrades. This method repositions finishing as a design and engineering responsibility, rather than a resource-intensive post-production process.

To advance the practical application of this approach, several steps are recommended. Industry-scale pilot runs on commercial Jacquard looms should be undertaken to confirm scalability. The development of advanced digital tools could support the creation of more randomised patterns and accurate drape simulations. Consumer testing will be essential to assess market acceptance, product durability, and maintenance behaviour over time. A comprehensive life cycle analysis, spanning from spinning to end-of-life disposal, should be conducted to quantify the long-term environmental impact. Finally, collaborative innovation between designers, manufacturing mills, and textile research institutes—such as BZU—will be key in building standardised, environmentally focused workflows for sustainable denim production.

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