



TOWARD A YARN GENOME: A UNIVERSAL FRAMEWORK FOR DESCRIBING TEXTILE YARN STRUCTURE

Review scientific paper
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ABSTRACT: Yarn structure is one of the most important factors influencing the mechanical, physical, and functional performance of textile products. Conventional yarn characterization primarily relies on individual parameters, including diameter, twist, hairiness, linear density, evenness, and tensile properties. Although these descriptors provide valuable information, none can independently represent the complex three-dimensional architecture of yarn or fully explain its structure–property relationships. Recent advances in digital imaging, three-dimensional characterization, and artificial intelligence have enabled the extraction of multiple structural features simultaneously, creating opportunities for more comprehensive yarn evaluation. This review introduces the concept of a Yarn Genome, a universal framework that integrates conventional and emerging structural descriptors into a multidimensional representation of yarn identity. Inspired by the Materials Genome Initiative, the proposed framework combines twist, diameter variation, fiber orientation, porosity, hairiness, surface chemistry, and structural complexity quantified using image-based descriptors such as entropy, fractal dimension, and texture analysis. The review summarizes conventional yarn descriptors, discusses modern characterization technologies, and highlights their roles in defining the proposed Yarn Genome. Finally, future perspectives involving artificial intelligence, digital twins, smart spinning systems, standardized Yarn Genome databases, and digital textile passports are presented. The proposed framework provides a conceptual foundation for next-generation yarn characterization, supporting predictive textile engineering, intelligent quality control, and data-driven textile manufacturing.

Keywords: Yarn Genome; yarn structure; structural descriptors; digital image analysis; textile characterization; artificial intelligence; porosity; fiber orientation; hairiness.

KA KONCEPTU GENOMA PREĐE: UNIVERZALNI OKVIR ZA OPISIVANJE STRUTURE TEKSTILNE PREĐE

APSTRAKT: Struktura pređe predstavlja jedan od najvažnijih faktora koji utiče na mehaničke, fizičke i funkcionalne karakteristike tekstilnih proizvoda. Konvencionalna karakterizacija pređe uglavnom se zasniva na pojedinačnim parametrima, uključujući



prečnik, uvoj, dlakavost, finost, neravnomernost i zatezna svojstva. Iako ovi deskriptori pružaju značajne informacije, nijedan od njih pojedinačno ne može u potpunosti da opiše složenu trodimenzionalnu arhitekturu pređe niti da objasni međusobni odnos između njene strukture i svojstava. Nedavni napredak u oblasti digitalnog snimanja, trodimenzionalne karakterizacije i veštačke inteligencije omogućio je istovremeno izdvajanje većeg broja strukturnih karakteristika, čime su otvorene nove mogućnosti za sveobuhvatniju analizu pređe. U ovom preglednom radu predstavljen je koncept Genoma pređe (Yarn Genome), univerzalnog okvira koji integriše konvencionalne i savremene strukturne deskriptore u višedimenzionalni prikaz identiteta pređe. Inspirisan inicijativom Materials Genome Initiative, predloženi okvir objedinjuje uvoj, varijaciju prečnika, orijentaciju vlakana, poroznost, dlakavost, površinsku hemiju i strukturnu složenost određenu primenom deskriptora zasnovanih na analizi slike, kao što su entropija, fraktalna dimenzija i teksturne karakteristike. U radu su dati pregled konvencionalnih deskriptora pređe, analiza savremenih metoda karakterizacije i njihov značaj za definisanje predloženog Genoma pređe. Na kraju su razmotrene buduće perspektive koje uključuju primenu veštačke inteligencije, digitalnih blizanaca, inteligentnih sistema pređenja, standardizovanih baza podataka Genoma pređe i digitalnih pasoša tekstilnih proizvoda. Predloženi okvir predstavlja konceptualnu osnovu za novu generaciju karakterizacije pređe i pruža podršku razvoju prediktivnog tekstilnog inženjerstva, inteligentne kontrole kvaliteta i proizvodnje zasnovane na podacima.

Ključne reči: Genom pređe; struktura pređe; strukturni deskriptori; digitalna analiza slike; karakterizacija tekstila; veštačka inteligencija; poroznost; orijentacija vlakana; dlakavost.

1. INTRODUCTION

Yarn is the fundamental structural element of textile products, linking individual fibers to finished fabrics [1-3]. Its structure governs mechanical, physical, and functional properties, including strength, comfort, permeability, durability, and dyeability. Consequently, yarn characterization has long been a key research area in textile engineering. Conventional descriptors such as diameter, twist, linear density, evenness, hairiness, and tensile properties remain essential for quality assessment. However, each describes only one aspect of the complex hierarchical fiber assembly, highlighting the need for a more comprehensive structural characterization framework [4].

Yarn is a heterogeneous three-dimensional assembly of fibers with varying orientations, packing densities, porosity, and migration paths [5]. Consequently, yarns with identical conventional parameters may exhibit substantially different mechanical, transport, and functional properties, demonstrating that no single descriptor can adequately represent their structural complexity.

Yarn characterization has evolved from conventional measurements of count, twist, diameter, and tensile properties to advanced techniques including optical microscopy, digital image analysis, three-dimensional imaging, and artificial intelligence. This

progression has shifted textile research toward integrated, multidimensional structural characterization (Figure 1).

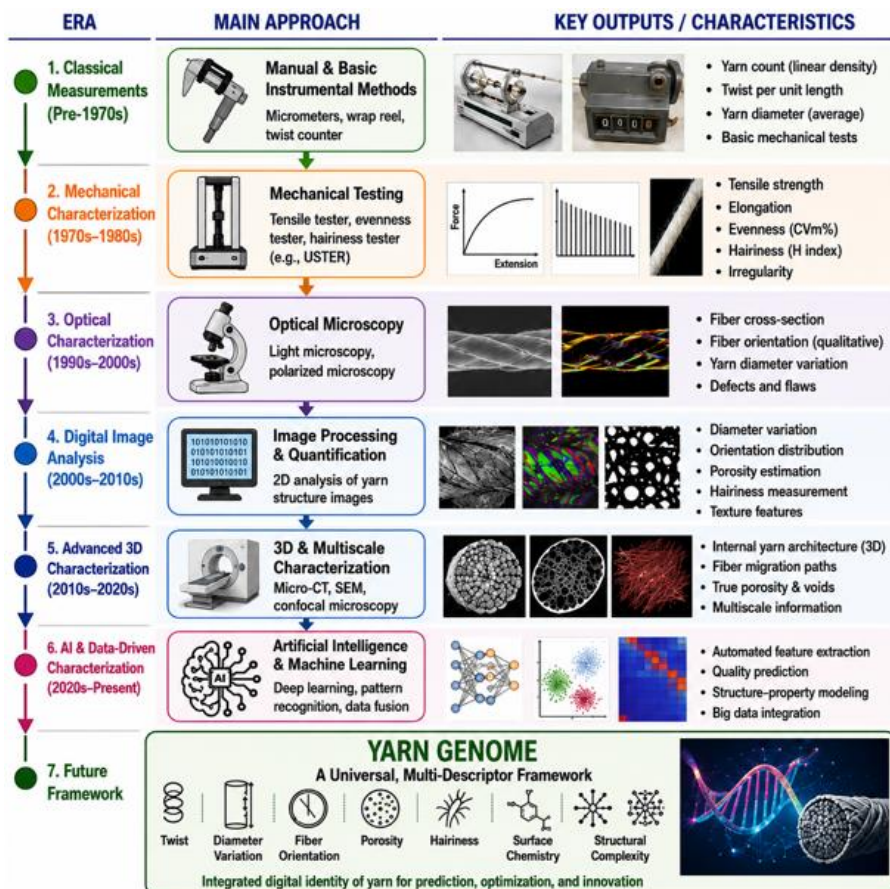


Figure 1: Evaluation of yarn characterization methods

Advances in digital imaging, computer vision, micro-CT, SEM, and artificial intelligence enable simultaneous extraction of structural descriptors such as fiber orientation, porosity, texture, and entropy, providing more comprehensive yarn characterization [6,7]. Nevertheless, current approaches remain fragmented, typically evaluating descriptors independently rather than as an integrated structural system.

Inspired by the Materials Genome Initiative (MGI), which integrates multidimensional descriptors to predict material performance [8], this review proposes the Yarn Genome—a universal framework combining conventional and image-derived structural descriptors to



establish a digital yarn identity for predictive modeling, intelligent quality assessment, digital twins, and AI-assisted textile engineering.

The objective of this review is therefore threefold: (i) to summarize conventional yarn structural descriptors and their limitations; (ii) to introduce the concept of a Yarn Genome as a comprehensive multidimensional framework for yarn characterization; and (iii) to discuss future opportunities for AI-driven textile engineering based on integrated structural descriptors.

2. CONVENTIONAL YARN STRUCTURAL DESCRIPTORS

Yarn structural characteristics govern both textile processing and final product performance. Conventional characterization relies on individual descriptors that quantify specific structural features and support quality control. However, these isolated measurements cannot fully represent the complex three-dimensional fiber organization, highlighting the need for integrated multidimensional structural characterization.

Yarn diameter is a fundamental geometric descriptor influencing fabric cover, mechanical properties, air permeability, thermal insulation, and dye penetration. It is commonly measured using optical microscopy, laser techniques, or image analysis. However, average diameter alone cannot adequately represent structural variability because yarn diameter fluctuates continuously due to irregular fiber arrangement and measurement conditions [9]. Twist, defined as the number of turns per unit length, is a key parameter controlling fiber cohesion, tensile strength, and yarn stability. Although higher twist improves fiber binding, excessive twist reduces softness and flexibility. Conventional measurements report only average twist, overlooking local variations and fiber migration that also influence yarn performance [9].

Hairiness describes fibers protruding from the yarn surface and influences abrasion resistance, pilling, friction, dye uptake, weaving performance, and fabric appearance. Commonly measured using optical or capacitive instruments, it characterizes only surface morphology and provides limited information about internal fiber arrangement and structural heterogeneity [10].

Yarn irregularity, commonly expressed as the coefficient of mass variation (CVm%), quantifies mass fluctuations along the yarn length. It influences tensile properties, dye uniformity, and fabric quality. Although modern evenness testers rapidly assess yarn uniformity, CVm% remains a statistical indicator and does not identify structural causes such as fiber migration, packing density, or diameter variation [11].

Fiber orientation describes the spatial arrangement of fibers within the yarn and strongly influences mechanical and transport properties. Although advanced techniques such as optical microscopy and micro-CT enable detailed visualization, quantitative evaluation remains challenging because fiber orientation continuously varies throughout the yarn structure [5].

Porosity governs transport properties within yarn and influences dyeing, finishing, filtration, and composite impregnation. Modern image analysis and micro-CT improve

pore characterization, but comprehensive evaluation requires integration with other structural descriptors within the proposed Yarn Genome framework [12].

3. TOWARD THE CONCEPT OF A YARN GENOME

Advances in imaging, computational modeling, and artificial intelligence have greatly enhanced yarn characterization by revealing structural features across multiple length scales. However, current approaches remain fragmented, lacking a unified framework to integrate diverse structural descriptors. A similar challenge was addressed by the Materials Genome Initiative (MGI), which introduced a descriptor-based approach combining experiments, simulations, and digital databases to enable data-driven prediction of material behavior and support digital twins, machine learning, and intelligent manufacturing systems (Figure 2) [8].

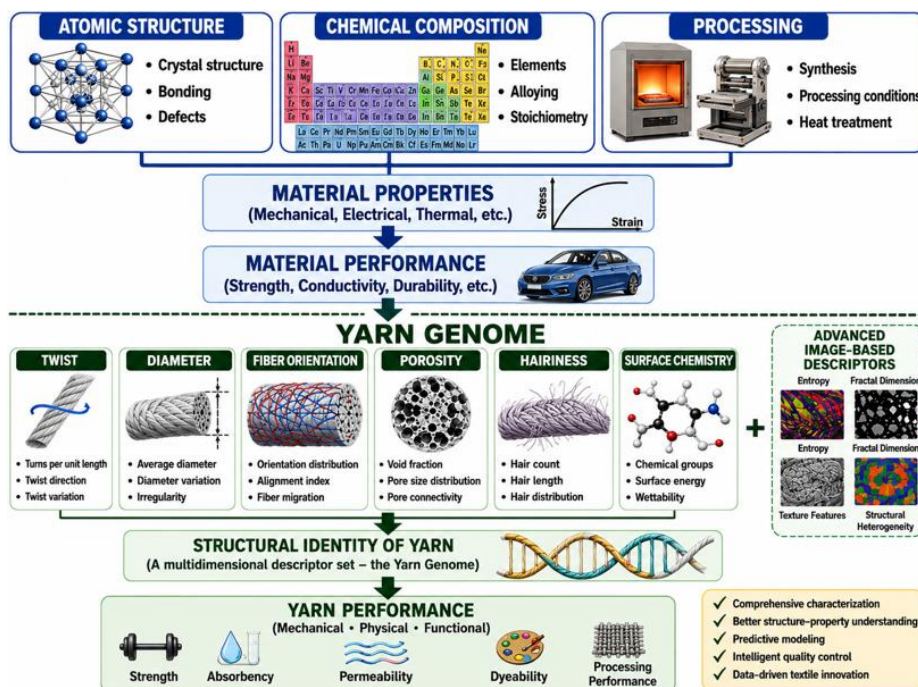


Figure 2: Analogy between the materials genome and the proposed Yarn Genome

The Materials Genome Initiative (MGI) demonstrated that complex materials require integrated descriptor sets rather than isolated parameters to accurately predict performance [8]. Similarly, textile yarns are hierarchical fibrous assemblies whose mechanical, physical, and functional properties arise from interactions among descriptors such as twist, diameter, fiber orientation, porosity, and hairiness rather than any single parameter [5]. While



conventional methods evaluate these descriptors individually, recent advances in digital image processing, micro-computed tomography, optical imaging, and artificial intelligence enable their simultaneous extraction, creating opportunities for integrated, descriptor-based yarn characterization.

4. COMPONENTS OF THE YARN GENOME

The proposed Yarn Genome integrates complementary structural descriptor groups into a unified framework that captures both external morphology and internal fiber organization. Inspired by the Materials Genome Initiative, it combines multiple measurable variables into a multidimensional structural fingerprint, providing a more comprehensive representation of yarn architecture than conventional individual descriptors.

Twist is a key structural parameter governing fiber cohesion and yarn stability. While conventional characterization reports average twist (TPM or TPI), it does not capture its spatial variability [9]. The proposed twist descriptor group includes twist level, angle, direction (S/Z), local variation, and distribution, collectively providing a more comprehensive description of fiber binding and its influence on yarn performance.

Yarn diameter is traditionally reported as an average value; however, it varies continuously because of drafting irregularities, fiber migration, and packing density variations [5,9]. The proposed diameter descriptor group includes average diameter, diameter variation, longitudinal profile, and diameter distribution, providing a more comprehensive characterization of structural uniformity, processing stability, and yarn geometry than a single average measurement.

Fiber orientation strongly influences yarn mechanical and transport properties [5]. The proposed fiber Orientation descriptor group includes orientation distribution, orientation tensor, alignment coefficient, fiber migration index, and orientation heterogeneity. Quantified using optical microscopy, digital image analysis, or micro-computed tomography, these descriptors comprehensively characterize the internal yarn architecture. The porosity descriptor group characterizes the internal transport network using descriptors such as total porosity, pore-size distribution, pore connectivity, tortuosity, and spatial porosity distribution, which are essential for predicting dyeing, finishing, filtration, and composite impregnation.

The hairiness descriptor group extends conventional hairiness evaluation by incorporating hair length distribution, protruding fiber density, surface fiber orientation, spatial clustering, and surface roughness, providing a more comprehensive description of yarn surface morphology and its influence on friction, abrasion resistance, pilling, and fabric appearance.

The surface chemistry descriptor group complements structural characterization by describing functional properties through descriptors such as functional groups, surface energy, wettability, chemical composition, plasma or enzymatic modifications, and polymer or nanoparticle coatings [13-15]. These descriptors establish a direct relationship between yarn architecture and functional performance, including dyeability, adhesion, and antimicrobial activity.

The structural complexity descriptor group incorporates image-derived descriptors that quantify yarn heterogeneity beyond conventional measurements. It includes entropy, fractal dimension, GLCM texture features, Local Binary Patterns (LBP), Gabor features, and wavelet features [16]. Automatically extracted through digital image analysis, these descriptors characterize structural randomness, complexity, and spatial organization, making them particularly suitable for machine learning and artificial intelligence applications.

The proposed Yarn Genome comprises seven descriptor groups: twist, diameter, fiber orientation, porosity, hairiness, surface chemistry, and structural complexity. By integrating these complementary descriptors into a unified structural fingerprint, the Yarn Genome provides a comprehensive representation of yarn identity and establishes a foundation for predictive modeling, digital twins, intelligent quality control, and AI-assisted textile engineering.

5. MEASUREMENT TECHNOLOGIES FOR YARN GENOME CHARACTERIZATION

Successful implementation of the proposed Yarn Genome requires characterization techniques capable of quantifying both conventional and advanced structural descriptors. While traditional textile testing remains essential, advances in imaging and computational analysis enable comprehensive extraction of structural information, making the integration of multiple measurement techniques fundamental to Yarn Genome characterization.

Optical microscopy is widely used for yarn characterization because it is simple, non-destructive, and enables quantitative evaluation of diameter, hairiness, fiber distribution, orientation, and texture through digital image analysis. Scanning electron microscopy (SEM) complements optical microscopy by providing high-resolution visualization of surface morphology, fiber interactions, roughness, coatings, and chemical modifications, making it particularly valuable for characterizing the external architecture and surface chemistry of the proposed Yarn Genome [17].

Micro-computed tomography (micro-CT) enables non-destructive three-dimensional visualization of internal yarn architecture, including fiber orientation, migration, packing density, and pore connectivity, making it essential for defining Yarn Genome descriptors [18]. Digital image analysis automatically extracts quantitative features such as diameter profiles, hairiness, orientation, porosity, and texture from yarn images with high repeatability and efficiency [9,12]. Advanced image-processing algorithms, including segmentation, entropy analysis, Gray-Level Co-occurrence Matrix (GLCM) [19], Local Binary Patterns (LBP), Gabor filters, and wavelet transforms, further quantify structural complexity, spatial heterogeneity, and local organization, providing descriptors unavailable through conventional textile measurements and supporting AI-driven Yarn Genome characterization.

Artificial intelligence represents the next stage of yarn characterization by integrating multiple Yarn Genome descriptors to predict yarn quality, mechanical properties, spinning defects, and processing performance. Machine learning and deep learning enable



automated analysis of multidimensional image-derived data, supporting predictive models and autonomous manufacturing. Together with advanced imaging techniques, these technologies provide the experimental and computational foundation for the Yarn Genome, enabling comprehensive digital characterization and intelligent textile engineering.

6. FUTURE PERSPECTIVES AND RESEARCH CHALLENGES

The proposed Yarn Genome establishes a conceptual foundation for next-generation digital textile engineering. By integrating multidimensional structural descriptors with artificial intelligence and advanced computational methods, it supports the transition from conventional yarn characterization to predictive, data-driven systems aligned with Industry 4.0 manufacturing.

Artificial intelligence (AI) is expected to play a central role in implementing the yarn genome by integrating multiple structural descriptors to predict yarn quality, mechanical properties, and processing performance. Machine learning and deep learning, particularly convolutional neural networks (CNNs), enable automatic extraction of complex structural features from textile images, improving prediction accuracy, automating quality evaluation, and reducing inspection time. These capabilities position AI as a key technology for future intelligent textile manufacturing.

Digital twin technology enables virtual representations of physical systems by integrating experimental data, computational models, and operational information. Within the proposed framework, the Yarn Genome can serve as the structural foundation for digital yarn twins, enabling simulation of yarn behavior under different conditions, optimizing spinning parameters, accelerating yarn design, and reducing experimental effort and manufacturing costs.

Future smart spinning systems will combine real-time sensing, machine vision, and multi-response optimization to continuously monitor yarn genome descriptors [20]. This enables autonomous adjustment of spinning parameters, improving process stability, minimizing material waste, reducing production variability, and shifting quality control from post-production inspection to real-time optimization.

Standardized Yarn Genome databases integrating conventional, image-derived, processing, and performance data are essential for supporting artificial intelligence, reproducibility, and data sharing. Furthermore, incorporating the Yarn Genome into digital product passports, together with IoT and cloud-based manufacturing, could enable complete digital traceability and promote transparent, data-driven, and sustainable textile production.

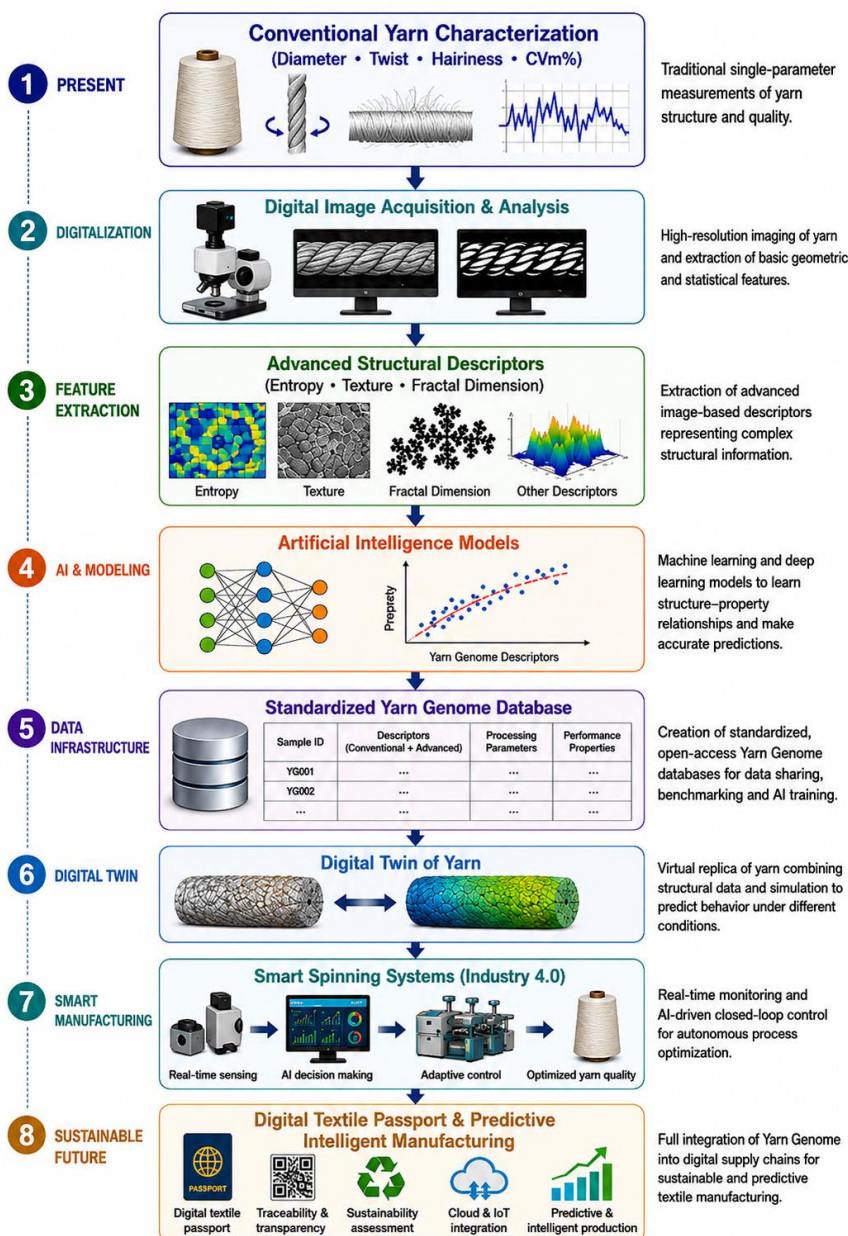


Figure 3: Future roadmap toward a universal Yarn Genome framework



7. CONCLUSION

Textile yarns are complex hierarchical structures whose behavior cannot be fully explained using isolated structural parameters. Conventional descriptors such as diameter, twist, hairiness, irregularity, fiber orientation, and porosity provide valuable information but describe only individual aspects of yarn architecture. This review introduced the Yarn Genome, a descriptor-based framework inspired by the Materials Genome Initiative that integrates conventional measurements with advanced image-derived descriptors, including entropy, fractal dimension, texture features, and surface chemistry, to establish a multidimensional representation of yarn identity. Advances in optical microscopy, SEM, micro-computed tomography, digital image analysis, and artificial intelligence provide the technological foundation for implementing this concept. Combined with machine learning, digital twins, standardized databases, and smart manufacturing, the Yarn Genome offers a promising framework for predictive textile engineering, intelligent quality control, and Industry 4.0. Future research should focus on descriptor standardization, large-scale Yarn Genome databases, and AI-driven prediction of yarn performance.

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