

Review

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Review

A Systematic Review of AI-Driven Prediction of Fabric Properties and Handfeel

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Abstract: Artificial intelligence (AI) is revolutionizing the textile industry by improving the prediction of fabric properties and handfeel, which are essential for assessing textile quality and performance. However, the practical application and translation of AI-predicted results into real-world textile production remain unclear, posing challenges for widespread adoption. This paper systematically reviews AI-driven techniques for predicting these characteristics by focusing on model mechanisms, dataset diversity, and prediction accuracy. Among 811 papers initially identified, 26 were selected for in-depth analysis through both bibliometric and content analysis. The review categorizes and evaluates various AI approaches, including machine learning, deep learning, and hybrid models, across different types of fabric. Despite significant advances, challenges remain, such as ensuring model generalization and managing complex fabric behavior. Future research should focus on developing more robust models, integrating sustainability, and refining feature extraction techniques. This review highlights the critical gaps in the literature and provides practical insights to enhance AI-driven prediction of fabric properties, thus guiding future textile innovations.

Keywords: fabric handfeel prediction; AI in textiles; textile property prediction; tactile simulation

1. Introduction

With rapid technological advancements, the application of artificial intelligence (AI) in the textile industry is becoming a forefront area of research and practice. AI has introduced unprecedented innovations in textile design, manufacturing, and quality control, particularly in predicting fabric properties and handfeel. Fabric properties, such as strength, elasticity, breathability, and handfeel characteristics like softness and roughness, are critical factors that determine the final performance of textiles [1]. Traditionally, the measurement and evaluation of these properties relied heavily on laboratory testing and expert judgment, which are not only time-consuming and costly but also inherently subjective [2,3]. As a result, there has been a growing interest in leveraging AI technology to automate the prediction of these properties, thus driving the industry towards greater efficiency, consistency, and sustainability.

In recent years, researchers have explored various applications of AI in predicting fabric properties and handfeel across multiple dimensions. For instance, machine learning models have been employed to analyze and predict the mechanical performance and sensory characteristics of fabrics, which have yielded significant results [4,5]. These models not only handle complex multidimensional data but, in some cases, exceed the accuracy of traditional methods [6]. Additionally, with advancements in big data and deep learning, AI models have shown tremendous potential in processing larger and more complex datasets [7]. However, despite these advancements, the application of AI in predicting fabric property faces several challenges, such as the lack of diversity in data, limited generalizability of the model, and neglect of the impact of environmental variables in real-world applications [5,7].

Most existing studies focus on predicting a single property or handfeel characteristics, with little attention given to a systematic review of AI technologies that are used to predict more than one fabric

property and handfeel itself. Different AI models perform differently depending on the type of fabric and properties, and their effectiveness is significantly influenced by the scale and diversity of the datasets used [8]. Moreover, the growing awareness of environmental sustainability has driven the development of new predictive models that cater to the demand for eco-friendly materials and technologies [7]. Therefore, a comprehensive review of AI-driven techniques to predict fabric properties and handfeel is not only essential for mapping out current research but also to provide critical insights into future research directions.

This study presents a systematic review of AI-driven techniques to predict fabric properties and handfeel by focusing on the mechanisms of these models, diversity and scale of the datasets, and the accuracy and practical effectiveness of the predictions. We will review successful cases in current research, analyze their applications and limitations, and explore ways to enhance model accuracy in various application scenarios. Additionally, this paper will discuss the potential applications of these technologies in environmental sustainability and future textile developments.

Following this introduction, Section 2 will discuss the application mechanisms of AI models in predicting fabric properties. Section 3 will review the current research, and focus on the performance of different models and their real-world applications. Section 4 will analyze the impact of dataset diversity and scale on the accuracy of model predictions. Finally, Section 5 will outline future research challenges and directions to promote the broader application of AI in the textile industry.

2. Materials and Methods

This study reviews the effectiveness of AI in predicting handfeel-related fabric properties, such as softness, stiffness, and drape. This method was chosen because it provides a systematic approach that ensures objectivity, rigor, and transparency while offering insights into theoretical knowledge and current trends and developments relevant to the research question [9]. Following PRISMA guidelines, we conducted a focused search on the Web of Science (WoS) database, and targeted studies with successful predictions of fabric properties. The review identified research work with a high accuracy (over 80%) in predicting attributes like tensile strength and elasticity by using datasets with a few dozen to several hundred fabric samples. In addition to the database searches, manual and reference list searches were conducted to identify additional papers. After the selection process, the identified studies were further analyzed by using quantitative and qualitative methods to help answer the primary research questions, as shown in Figure 1.

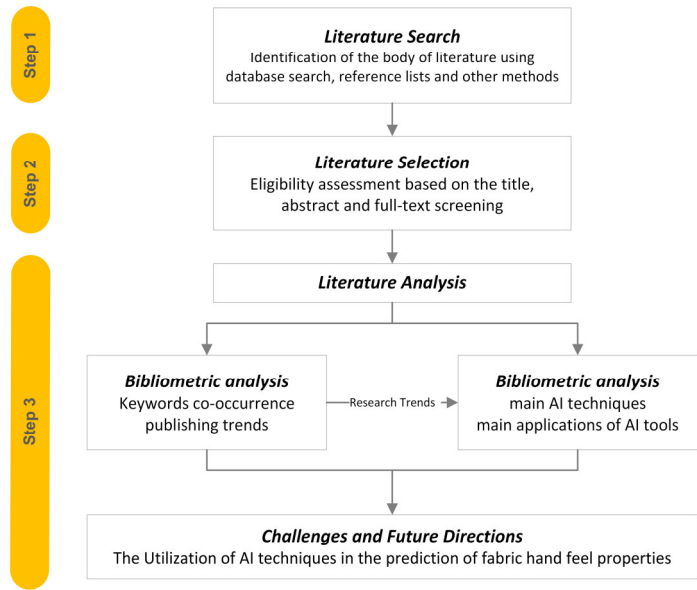


Figure 1. Visual flow of research process.

2.1. Forming Literature

The use of AI in measuring and predicting fabric properties is extensive, which complicates the identification of relevant studies on handfeel. To refine the literature search, we focused on three key categories: (1) handfeel measurement and evaluation systems, (2) fabric properties and predictive features, and (3) AI and machine learning models. These areas are integral to tactile perception research. The search was confined to publications from 2014 to August 2024 to ensure the inclusion of the most recent findings. The search criteria are detailed in Table 1.

Table 1. Search criteria.

Source	Source Criteria
Web of Science	(a) Research category: Materials Science, Textiles; Computer Science, Software Engineering; Materials Science, Composites (b) Type of paper: journal articles and proceedings papers (c) Years of publication: from 2014 to August 2024 (d) Language: English
ScienceDirect	
Google Scholar	
Association for Computing Machinery	

The initial search was conducted on the WoS database, which was chosen for its peer-reviewed content and detailed categorization by research area, which are crucial for finding articles on fabric handfeel. The keywords were divided into two groups: one that targets AI tools and the other on fabric measurement and prediction terms. The search string included "artificial intelligence", "machine learning", "neural network", and other related terms (Figure 2). As shown in Figure 3, the initial search yielded 811 results from the WoS database that met the search criteria, followed by a rigorous literature selection process. The identified studies were screened according to the inclusion criteria in Table 2. Papers that are not related to the textiles industry were excluded, and only English-language papers were retained, which resulted in the elimination of 635 items to provide 176 papers. Title and abstract reviews eliminated 112 papers to further reduce the number of studies to 64 relevant papers. Due to 11 reports not being retrievable, the number of papers was reduced to 53 for eligibility assessment. A full-text assessment eliminated an additional 32 papers that did not directly contribute to the research question, but originated instead in unrelated disciplines like computer science or other material sciences.

Table 2. Search criteria.

Inclusion Criterion	Value
Papers related to the textiles industry	Include
Papers written in the English language	Include
Title includes at least one searched keyword	Include
Abstract includes at least one searched keyword from each topic	Include
Abstract is relevant to the research question	Include
Papers that are not accessible in full text	Exclude
Full text is relevant to the research question	Include

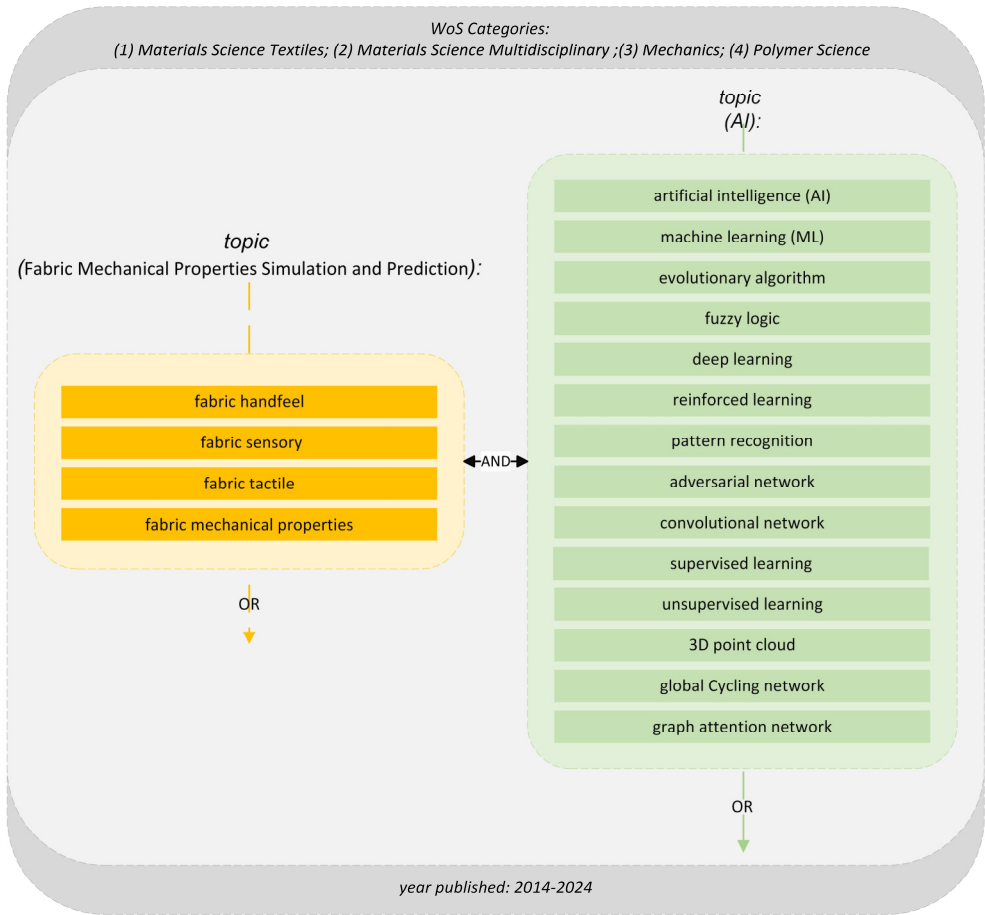


Figure 2. Illustration of the literature search domain and topics.

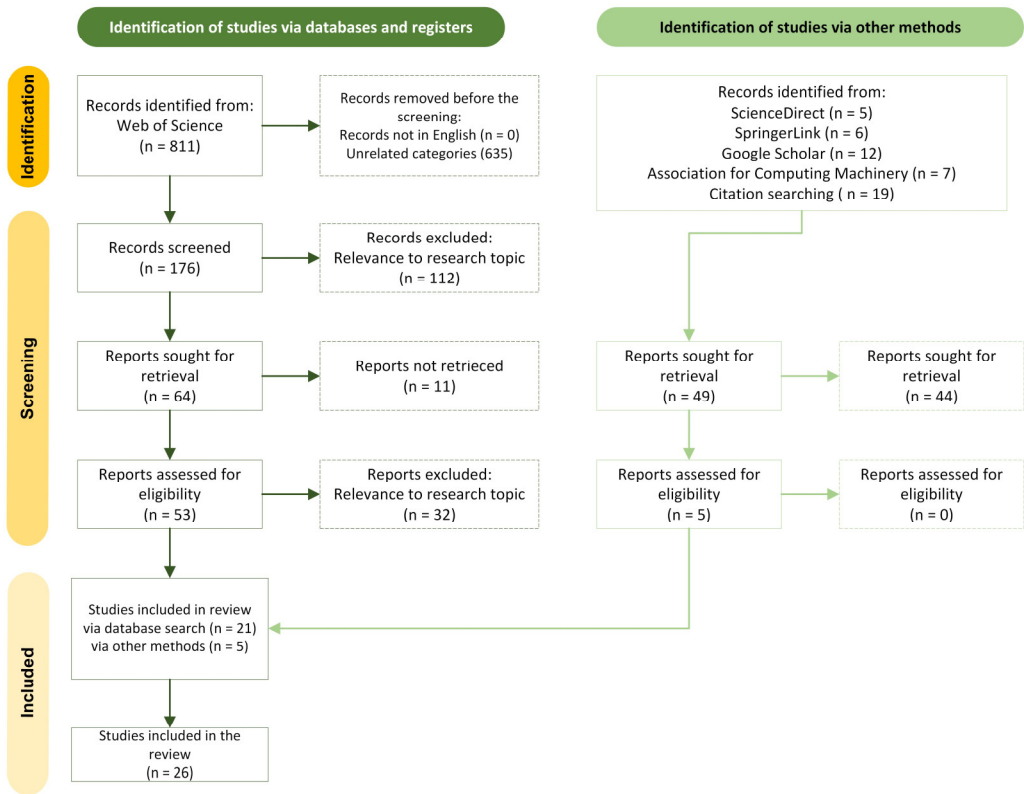


Figure 3. Flowchart of study identification and screening process for literature review.

Concurrently, an unstructured search that used the same keywords was conducted in different online repositories and Google Scholar to identify additional potentially relevant papers. This approach contributed an additional 49 papers. Full-text screening process was applied to papers collected from the other sources. After the screening, 5 papers met the inclusion criteria. Ultimately, 5 papers from other sources were included in the review and in the end, 26 studies were used for the analysis (Figure 3).

2.2. Analyzing Literature

The research process was conducted in three stages. First, extensive literature searches were performed to identify relevant studies. This was followed by a two-step screening process: an initial review of the titles and abstracts to filter out irrelevant studies, and a subsequent full-text assessment to ensure that the remaining studies directly addressed the research questions. Finally, a data analysis was independently carried out, with repeated validations to ensure accuracy and reduce bias.

From this process, 26 studies were selected for a detailed analysis with the use of both quantitative and qualitative methods. The quantitative analysis, which uses bibliometric techniques, focused on publication trends, citation patterns, and key research topics by analyzing the publication data, citations, and keywords. This provided a systematic overview of the field.

The qualitative analysis further explored these findings to offer deeper insights into the themes identified through the quantitative methods. Content analysis was used to systematically review AI-driven techniques for predicting the characteristics, which focused on the model mechanisms, dataset diversity, and prediction accuracy. This dual approach highlighted the current state of the technology and identified the main challenges in this area.

3. Results and Analysis

3.1. Bibliometric Analysis

3.1.1. Publication Trends

This study focuses on literature from the ten-year period between 2014 and 2024. Notably, there has been a significant increase in relevant publications from 2021 to 2024, with 10 papers (41%) being published during this time, see Figure 4. This trend underscores the novelty of the research area, and emphasizes the need for a comprehensive review. The analysis found that 23 of the 26 papers are journal articles, predominantly published in 16 different journals. The "Textile Research Journal" published 4 articles, which indicates that this journal prioritizes prediction techniques for textile performance. Other journals, like ACM Transactions on Graphics and Indian Journal of Fibre & Textile Research, also published multiple articles, which reflects a broader interest in AI applications for predicting and evaluating fabric hand.

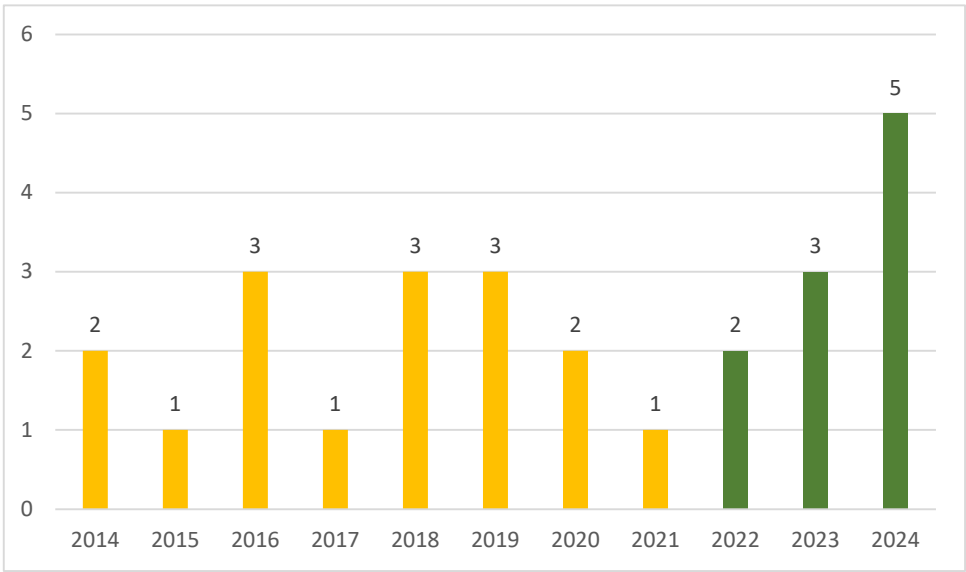


Figure 4. Number of related articles published each year.

3.1.2. Keyword Analysis

The keywords were analyzed by using the full counting method, which highlights significant relationships within a dataset. The analysis identified 13 keywords with more than two occurrences, to form a visual network that categorizes the research into four clusters (Figure 5). The most frequent keywords are: "fabric hand" and "objective evaluation", which shows a strong focus on the quantitative assessment of fabric properties by using AI tools. The clustering revealed three main research themes: "AI-driven evaluation and prediction for handfeel characteristics" which focuses on tactile comfort and objective evaluations; "AI-driven evaluation and prediction for predicting fabric mechanical properties," which emphasizes the mechanical properties and performance; and "AI-driven predictive modeling for fabric drape", which centers on fabric drape and simulation processes.

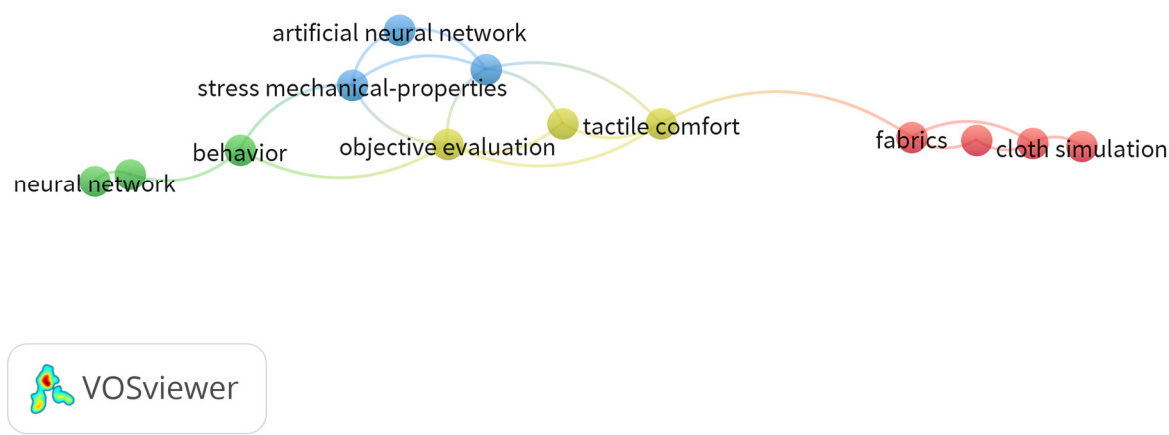


Figure 5. Visualization of keyword network.

Based on the keyword co-occurrence in the analyzed sample, two methods for the network visualization were considered: (1) automatically extracting frequently used terms from titles or abstracts, and (2) generating data maps by using directory metadata keywords [10]. This study employs the second method to clearly identify the primary research themes by using predefined

keywords that align with the main topics. The bibliographic metadata was gathered by using EndNote and analyzed with VOSviewer.

3.2. Content Analysis

3.2.1. Measurement and Evaluation Systems

- **Objective and Subjective Evaluations of Fabric Properties**

The evaluation of fabric properties and handfeel is critical in textile research, which encompasses both subjective and objective methods. The Kawabata Evaluation System (KES) is a key tool for measuring mechanical properties related to fabric handfeel, including bending, shear, tensile, and compression stiffness, along with surface smoothness and friction [11]. Other systems like Fabric Assurance by Simple Testing (FAST) [12] and the Fabric Touch Tester [13] provide objective evaluations as well. The Fabric Touch Tester, for instance, assesses compression, surface friction, thermal, and bending properties to offer a comprehensive index of fabric handle characteristics [14].

Recent research has increasingly integrated subjective and objective methods to combine sensory analysis with physical measurements. [15] highlighted individual differences in tactile perception by analyzing finger sliding over fabrics, using KES to measure physical properties and proposing skin vibration as an alternative measure for fabric handfeel. Additionally, innovative methods like the three-dimensional (3D) drape model, which uses a principal component analysis (PCA), have been explored for the objective assessment of fabric handfeel [16].

- **Innovative Methods for Drape Measurement**

Recent research has introduced advanced methods to improve the accuracy and applicability of fabric drape measurements. One method uses a reciprocating device to simulate fabric movement to identify key factors like node number, amplitude, and the position of the first node, which are crucial for assessing dynamic drape [17]. Another approach combines multidirectional stiffness and drape measurement into a single method by introducing parameters like projection area and length, which correlate well with bending performance and drape, thus offering a more comprehensive evaluation than traditional methods [18].

A learning-based method that uses a drape tester adopts a model-in-the-loop strategy, which uses regression-based neural networks to estimate the simulation parameters, thus enhancing fabric simulation accuracy [19]. Additionally, 3D-printed human models enable more realistic static and dynamic drape evaluations, which can capture 3D fabric behavior [20]. Methods that use Kinect sensors provide non-contact 3D drape measurements, thus correlating well with traditional and subjective evaluations [21]. The Texttechno Drapetest device uses a digital image analysis system and laser triangulation sensor in Christ et al. [21] to measure the drape effects, thus offering insights into controlling fabric behavior during 3D shaping. [22] Lastly, Kim [23] used a method that involves a depth camera with an elevating device to compare traditional drape testing with 3D scanning, thus adding valuable insights into the drape phenomena of fabric through 3D analysis.

3.2.2. Fabric Properties and Predictive Features

In AI-driven techniques to predict fabric properties and handfeel, key attributes like mechanical and sensory properties are vital for accurate modeling and predicting tactile comfort and overall handfeel.

Texture, weave parameters, tactile comfort, surface friction, and functional surface treatments are key factors in AI-driven predictions. Seçkin et al. [7] used machine learning algorithms like XGBoost and random forest (RF) to analyze texture and weave parameters from microscopic images, and created a dataset with 458 inputs and 4 outputs, which led to accurate predictions of fabric properties and consistent product quality. Tadesse et al. [23] and Ahirwar and Behera [24] focused on mechanical properties and handfeel attributes, and utilized tools like KES-FB, PCA, artificial neural networks (ANNs), and adaptive network-based fuzzy inference systems (ANFISs) to predict tactile comfort, thus highlighting the importance of both subjective and objective assessments. Surface friction, crucial for comfort, was modeled by Ezazshahabi et al. [25] who used a genetic algorithm to

effectively predict tactile characteristics based on structural parameters, which streamlines design processes. Additionally, Tuigong and Xin [24] showed that mechanical and surface properties can be used to predict fabric hand stiffness, thus further highlighting the role of these characteristics in fabric property evaluation. Functional surface treatments, including finishes and coatings, significantly impact fabric handfeel, as shown by Tadesse et al. [27], who used fuzzy logic and neural networks to predict hand values to optimize production for consumer preferences [25]. Thermal physiological properties, vital for comfort, were integrated into handfeel models by Xue et al. [28], thus enhancing the prediction of consumer preferences [26]. Finally, Das and Shanmugaraja [27] predicted weave patterns, which are essential for tactile and aesthetic quality by using ANNs to improve accuracy and efficiency in fabric production.

3.2.3. AI and Machine Learning Models

In AI-driven predictions of fabric properties and handfeel, a number of different AI and machine learning models are used to enhance accuracy and efficiency in the textile industry. Automated machine learning (AutoML) technologies simplify model selection and optimization, as seen in Metin and Bilgin [5] who evaluated seven open-source tools. EvalML, an AutoML library, excels in determining the mean absolute error (MAE), while AutoGluon has the best performance in calculating the mean absolute percentage error (MAPE), root mean square error (RMSE), and R-squared, thus highlighting the need to balance accuracy with computational efficiency in predicting fabric quality [5].

Machine learning algorithms like XGBoost and RF have proven effective in predicting texture and weave parameters. In Seçkin et al. [7], XGBoost achieved a 0.987 accuracy in texture classification, and RF has the lowest MAE in specific mass prediction, which show the potential of these algorithms in enhancing the accuracy of production processes and ensuring a consistent fabric handfeel.

Deep learning models, including convolutional neural networks (CNNs) and hybrid YOLOv4-R-CNN models, are used to detect fabric defects, and crucial for maintaining high fabric quality [28,29]. These models also predict material parameters like stiffness and damping, which are essential for accurate fabric simulations in virtual environments. Mao et al. [30] used deep learning models such as Transformer, to obtain a 99.01% accuracy in predicting key material parameters, thereby improving the realism and efficiency of fabric simulations.

ANNs are extensively employed to predict various fabric properties, including thermal characteristics, air permeability, and tensile strength. Jhanji et al. [33] highlighted the effectiveness of ANNs in modeling complex and nonlinear relationships, while Erenler and Oğulata [34] achieved a high correlation ($R = 0.99366$) in predicting air permeability based on factors like weft count and weave pattern. Kothari and Bhattacharjee [31] applied ANNs to predict thermal properties and capture the intricate relationships between fabric structure and thermal behavior more robustly than traditional methods. Ahirwar and Behera [24] showed a strong correlation (0.82) between ANN predictions and subjective assessments of fabric handfeel, while Elkateb [4] validated the utility of ANNs in predicting mechanical properties like tensile strength and bending stiffness, which underscores their potential to enhance customer satisfaction through accurate predictions of handfeel [4,32].

4. Applications

The themes identified through the application of AI include: (1) predictive modeling for simulation, (2) optimization of fabric properties, and (3) evaluation and classification driven by AI, which are analyzed in depth in this section (Figure 8). Within each theme, the following aspects are reviewed:

1. The application of AI algorithms for specific fabric properties;
2. How AI has overcome challenges in the prediction of fabric properties, particularly with complex datasets; and
3. Modifications made to AI algorithms to accommodate specific application domains.



Figure 6. Overview of primary identified uses for AI in predicting fabric handfeel.

4.1. Prediction of Fabric Handfeel Characteristics

AI techniques such as extreme learning machines, genetic algorithms, fuzzy logic, ANFISs, and deep learning have been used in studies to predict various fabric properties with high accuracy. These methods analyze features derived from tactile sensors, visual attributes, and mechanical measurements to predict the tactile qualities of fabrics. The datasets used in these studies vary widely, which range from a few dozen textile samples to tens of thousands of images, thus reflecting the scalability and adaptability of AI techniques in this field (Table 4).

Table 3. Summary of key studies of AI techniques for predicting fabric handfeel characteristics.

Fabric Properties	Predictive Features	AI & Techniques	Dataset Size	Accuracy Rate	Reference
Texture recognition (roughness, smoothness)	Spatiotemporal spike patterns derived from tactile sensors	Extreme learning machine	10 graded textures with 50 data samples	92% classification accuracy	Rasouli et al. [33]
Tactile properties (softness, smoothness,	Relations between tactile properties and total preference for men’s suits	Genetic algorithm, fuzzy	50 textile fabrics with various tactile properties	Close to genetic algorithm solution: 95% (accuracy in	Xue et al. [34]

fullness, flexibility, delicacy, lightness, resiliency)		comprehensive evaluation		weight distribution)	
Tactile properties (softness, smoothness, flexibility, etc.)	Visual features (drape, fit at abdomen and hip, wave size, etc.)	ANFISs	18 textile samples used for training; 3 additional samples for testing	Predictive errors for tactile properties do not exceed 1 on an 11-point scale	Xue et al. [35]
Tactile properties	Visual features	Deep learning, ResNet-50	11,328 images (training), 2832 images (testing)	99.3% accuracy in woven fabric types; error level below 10% in yarn quality evaluation	Gültekin et al. [36]
Mechanical properties (tensile, shearing, bending, compression, surface friction)	Total hand value and tactile comfort scores predicted by using low-stress mechanical properties	Artificial neural networks, ANFISs	486 measurements: 15 mechanical properties * 6 samples * 3 replicas * 2 directions	ANN RMSE: 0.014; ANFIS RMSE: 0.0122, with significantly lower errors than standard deviations (ANN: 0.644, ANFIS: 0.85)	Tadesse et al. [37]
Tactile comfort (warm-cool, itchy-silky, etc.)	Hand value and total hand value predicted from sensory attributes	Fuzzy logic model, ANN	9 functional fabrics, various finishing parameters	FLM RMSE: 0.21; ANN RMSE: 0.13; FLM RMPE < 10%; ANN RMPE: 2.24%	Tadesse et al. [25]

In the application of AI for predicting fabric handfeel characteristics, various techniques have been employed for different fabric properties. For instance, Rasouli et al. [33] used extreme learning machines to classify textures such as roughness and smoothness, and obtained a 92% rate of accuracy with a dataset of 10 graded textures. Xue et al. [34,35] applied genetic algorithms and ANFISs to predict tactile properties like softness and flexibility, with their models obtaining close to a 95% accuracy in weight distribution and minimal predictive errors on an 11-point scale, respectively. Gültekin et al. [36] utilized deep learning techniques, specifically ResNet-50, to predict the tactile properties based on visual features, and obtained a 99.3% accuracy rate in woven types of fabric and an error level less than 10% in yarn quality evaluation. Finally, Tadesse et al. [25,37] combined ANNs with fuzzy logic models to predict tactile comfort scores and mechanical properties, with their models showing low error rates and high prediction accuracy.

4.2. Prediction of Fabric Mechanical Properties

Fabric mechanical properties such as shear strength, elasticity, bending stiffness, and tensile strength are crucial for determining the durability, functionality, and application suitability of textiles. Traditional methods of determining these properties often involved complex physical tests, which can be time-consuming, costly, and sometimes less adaptable to varying conditions. AI techniques are a promising alternative, which allow more efficient, accurate, and scalable predictions of the mechanical behaviors of fabric. This approach not only enhances the accuracy of material assessments but also facilitates the development of new textile materials with tailored mechanical characteristics.

Table 4. Summary of key studies of AI techniques for predicting mechanical properties of fabric.

Fabric Properties	Predictive Features	AI & Techniques	Dataset Size	Rate of accuracy	Reference
Fabric Shear and Deformation	Shear force, deformation patterns, normal stress, von Mises stress	Finite element analysis, Bernoulli-Euler beam theory, Coulomb's friction model	Multiple shear angles simulated; detailed yarn and fabric unit cells analyzed	Good agreement between finite element analysis and theoretical predictions, accuracy rate not explicitly stated but shown in comparisons	Basit and Luo [38]
Fabric Strength	Bursting Strength, Tensile Strength	Neural network, regression models	20 fabric samples	R ² = 0.765 (regression model), fuzzy logic close to real values	Kilic [39]
Elastic Properties	Warp and weft elasticity, Bias distortion, Pilling prediction from fabric design features	Automated machine learning, multi-target regression using deep artificial neural network	8650 fabric examples	NMAE: 4% for weft elasticity, 11% for pilling, 87% accuracy for textile composition	Ribeiro et al. [40]
Air permeability, Porosity	Fiber distribution, areal weight, texture features	Artificial neural networks	192 image frames	High regression (R=0.99 for air permeability)	Gültekin et al. [36]
In-Plane Shear Properties	Shear force, deformation under bias-extension test	Finite element analysis, analytical methods	Various textile composite reinforcements and preregs	Agreement between experimental and simulated shear behavior	Boisse et al. [41]
Bending Stiffness	Multi-view depth images of draped fabric specimens	Deep neural networks, Simulation-in-the-loop	618 real-world fabrics; 2.3 M synthetic depth images	Improved simulation fidelity; exact accuracy rate not stated but significant improvement over traditional methods	Feng et al. [19]
3D Textile Architecture	Yarn paths, weave initial architecture	Convolutional neural networks, long short-term memory	4000 weaving architectures	Stiffness properties prediction error < 10%	Koptelov et al. [42]
Yarn-Level Fabric Mechanics	Stiffness, Nonlinearity, Anisotropy of knitted fabrics	Yarn-level simulation, thin-shell model, parameter fitting	33 different knitted fabrics	Avg. error: 17.59% ± 8.33% for stretch force, 16.84% ± 8.11% for compression	Sperl et al. [43]

Mechanical Properties of Woven Composites	Fiber angles, resin material parameters, and effective modulus	Convolutional neural networks, finite element analysis	3,000 woven fiber composites	Average error < 5% compared to FEM results	Hsu et al. [44]
Textile Polymer Composite Materials	Tensile strength, compressive strength, bending strength, elongation at break	Multi-objective optimization, neural networks, support vector machines	420 samples with 11 physical characteristics	Optimized ANN accuracy: 90.2%; SVM accuracy: 89.9%	Malashin et al. [45]

The AI-driven prediction of the mechanical properties of fabrics has been used across various types of fabric with notable success. Basit and Luo [38] used a finite element analysis (FEA) along with the Bernoulli-Euler beam theory and Coulomb's friction model to accurately predict shear force and deformation patterns. Kilic [39] applied neural networks and regression models to predict fabric strength by focusing on bursting and tensile strength, and obtained an R^2 of 0.765 and close-to-real values with fuzzy logic, thus demonstrating the potential of AI in predicting strength. Ribeiro et al. [40] used automated machine learning and deep neural networks to predict warp and weft elasticities, and obtained a normalized mean absolute error (NMAE) of 4% and 87% accuracy for textile composition, thus underscoring the accuracy of AI in predicting elasticity. Gültekin et al. [36] effectively modeled air permeability and porosity by using ANNs, and obtained a high regression value ($R=0.99$).

In terms of bending and stiffness properties, Feng et al. [19] utilized deep neural networks and simulation-in-the-loop, and significantly improved simulation fidelity in predicting bending stiffness, while Koptelov et al. [42] achieved less than 10% error in predicting 3D textile architecture with the use of CNNs and LSTM networks, thus highlighting the capability of AI in handling complex structural properties.

For comprehensive mechanical properties, Boisse et al. [43] showed that there is a strong agreement between experimental and simulated in-plane shear properties by using FEA and analytical methods. Sperl et al. [43] predicted the stiffness, nonlinearity, and anisotropy in knitted fabrics with yarn-level simulation and thin-shell models. They reported an average error of 17.59% for the stretch force and 16.84% for compression. Hsu et al. [44] combined CNNs with FEA to predict woven composite properties with less than 5% error, while Malashin et al. [45] obtained an accuracy of 90.2% with neural networks and 89.9% with support vector machines in predicting tensile strength, compressive and bending strength, and elongation in textile polymer composites. These studies collectively show the efficacy and versatility of AI in predicting the different mechanical properties of fabric with a high degree of accuracy.

4.3. Prediction of Fabric Drape

The prediction of fabric drape is a crucial aspect of textile engineering, as drape characteristics significantly influence the aesthetic and functional qualities of garments and other textile products. Traditionally, fabric drape has been assessed through physical testing methods, which, while effective, can be labor-intensive and limited in scope. The integration of AI to predict fabric drape has provided new possibilities for more accurate, efficient, and scalable assessments. AI techniques such as fuzzy logic, finite element method (FEM), and CNNs have been employed to predict various drape-related properties, which range from drape coefficients and flexural rigidity to garment fit and tactile sensation.

Table 5. Summary of key studies of AI techniques for predicting fabric drape.

Fabric Properties	Predictive Features	AI & Techniques	Dataset Size	Accuracy Rate	Reference
Fabric Drape	Drape coefficient, flexural rigidity, tensile elongation	Fuzzy logic, image analysis	20 fabric samples	Fuzzy logic method provides results close to those with Cusick's method (accuracy within 1%)	Kilic [39]
Drape Behavior of 3D Woven Fabrics	Shear force, tensile, and bending behavior of 3D woven fabrics	FEM, shell elements, hyperplastic model	Various textile composite reinforcements	Validation against experimental results with good agreement	Hübner et al. [46]
Fabric Drape Behavior	Drape coefficient, node number, drape distance ratio, folds depth index	Fuzzy logic	63 woven fabrics	High correlation: DC (0.943), NN (0.936), DDR (0.969), FDI (0.946)	Hamdi et al. [47]
Garment Fit and Drape Characteristics	Fit score evaluation based on body dimensions and drape simulation	ANN, drape simulation	15-17 sizes for training, multiple body models	Not explicitly stated, but improved fit scores compared to traditional methods	Oh and Kim [48]
Fabric Drape and Mechanical Properties	Drape coefficient, stretch stiffness, bending stiffness	CNN with ResNet-18 and self-attention mechanisms	8 fabric samples (5 knit, 3 woven)	NMAE for AI-based drape: 3–51%; for PT-based drape: 2–11%	Youn et al. [6]
Drapability and Tactile Sensation (Softness)	Drape coefficient, softness	Fuzzy C-means clustering, ANN	777 fabric samples	ANN prediction accuracy: 83.5%	Lee et al. [16]

The AI applications for predicting fabric drape have shown significant advancements across various studies, with each focusing on different aspects of drape and using different techniques. Kilic [39] employed fuzzy logic combined with image analysis to predict fabric drape coefficients, and obtained an accuracy within 1% of that with the traditional Cusick's method. This approach shows the potential of AI to closely replicate established physical testing methods. Hamdi et al. [47] also used fuzzy logic to predict drape behavior in woven fabrics, and obtained high correlations across multiple metrics such as drape coefficient and folds depth index, thus further reinforcing the reliability of AI in accurately modeling drape characteristics.

Hübner et al. [46] focused on the drape behavior of 3D woven fabrics by using FEM and a hyperelastic model, and validated their simulations with the experimental results. They highlighted the effectiveness of AI models in simulating complex drape behaviors, which is crucial for advanced textile engineering. In the realm of garment fit and drape characteristics, Oh and Kim [48] applied ANNs in combination with drape simulation, which leads to improved fit scores compared to traditional methods, although specific accuracy rates were not detailed.

Youn et al. [6] expanded the scope by using CNNs with ResNet-18 and self-attention mechanisms to predict both the drape and mechanical properties of fabrics. Their work achieved normalized MAEs that range from 3% to 51%, thus showing the versatility of AI in handling multiple fabric characteristics simultaneously. Finally, Lee et al. [16] integrated fuzzy C-means clustering with ANNs to predict drapability and tactile sensation, particularly softness, with an accuracy of 83.5% across 777 fabric samples. This study underscores the effectiveness of AI in evaluating not only the drape but also the tactile qualities of fabrics.

5. Challenges and Future Directions

5.1. Challenges

Based on the results of the literature review presented in this study, three specific sets of challenges (which correspond to the identified application domains) are summarized: predicting fabric handfeel characteristics, the mechanical properties of fabric, and fabric drape.

Predicting Fabric Handfeel Characteristics

AI models often struggle with accurately predicting fabric properties when the training data lacks sufficient representation of the input parameters. This limitation is particularly evident in online shopping environments, where assessing tactile properties like softness and texture without physical interaction is challenging. The nonlinearity of fabric properties complicates the modeling process, thus making it difficult to achieve high accuracy with minimal error. Additionally, fabric stiffness introduces variability in stretch predictions, which requires models to account for this factor. Existing equations for handfeel may not be universally applicable, which requires the development of new equations tailored to different types of fabric for more accuracy.

Predicting Fabric Mechanical Properties

The accuracy of predictions greatly relies on the availability of large and diverse datasets. Insufficient or biased data can lead to significant inaccuracies. The complex, nonlinear relationship between fabric properties and mechanical behaviors poses a challenge in modeling, so that advanced techniques are often required to manage the extensive parameter spaces involved. Hardware limitations and the current state of cloth simulation technologies further impact prediction accuracy, thus making it difficult to obtain realistic simulations of fabric behaviors. Models must also effectively account for the interdependencies between properties such as stiffness, stretch, and tensile strength while ensuring robustness across various fabric compositions and structures.

Predicting Fabric Drape

Fabric stiffness plays a crucial role in determining the accuracy of predictions of drape, thus complicating the modeling of these interactions. Discrepancies often arise between simulated draping behavior and actual fabric performance, which highlights the difficulty of replicating real-world scenarios. Effective predictive modeling requires extensive and diverse datasets for training and validation; however, biased or insufficient data can undermine prediction accuracy. The nonlinear relationship between fabric properties and drape shapes creates a vast parameter space, which makes simulations both computationally costly and complex to manage. Additionally, limitations in hardware and current cloth simulation technologies affect the fidelity of drape predictions. Achieving consistent geometric texture and pattern regularity in fabric drapes is difficult due to the unpredictable effects of stitching and fabric properties. Ensuring that models generalize well across different types of fabric, while maintaining high accuracy with minimal error, remains a significant challenge, particularly when predicting properties in both the warp and weft directions.

5.2. Future Research Directions

Future research needs to address some of the identified challenges in this study by advancing AI and fabric handfeel. They can do so by using measuring and predicting technologies and their integration. Several promising directions are outlined below.

- **Multidimensional Strategies for Optimizing Accuracy of AI Models**

Future investigations should focus on enhancing the accuracy of AI models. Increasing the diversity and size of training datasets through synthetic data generation can improve generalization and accuracy for various types of fabric. Advanced feature extraction techniques, such as multi-scale methods and image processing, can capture the microstructural characteristics of fabrics, thus improving the ability of models to handle delicate or complex materials. Moreover, integrating different modeling strategies, such as combining linear regression, neural networks, and fuzzy logic, could create more robust hybrid models for accurate predictions of the mechanical properties of fabric.

- **Advanced Dynamic Simulation Techniques and Their Application in Innovative Clothing Design**

Advancements in dynamic drape testing should emphasize the development of advanced virtual methods to evaluate textile draping under various dynamic conditions. Testing fabrics with different movements and body positions can significantly enhance the functionality and ergonomic properties of clothing. Incorporating dynamic sensors and high-frame-rate imaging will enable the real-time capture of textile drape and deformation information, thus enhancing the authenticity and accuracy of simulations. New approaches, such as using advanced machine learning algorithms to predict fabric behavior under novel conditions, can further refine the simulation of real-world scenarios, thus enhancing decision-making in apparel design.

- **Predicting Mechanical Properties of Fabrics Using Advanced Computational Models**

Developing comprehensive bidirectional models to predict the different mechanical properties of fabrics, such as tensile strength and bending stiffness, can be a significant step forward. These models address the limitations of conventional approaches by capturing the intricate interactions among different properties, thus improving prediction accuracy. Integrating genetic algorithm-optimized neural networks (GA-ANNs) can enhance model robustness, which would allow for better accommodation of nonlinear fabric dynamics. This approach not only increases predictive accuracy but also reduces overfitting, thus ensuring resilience across different types of fabric and conditions.

- **Enhancing Visual-Tactile Correlation Models in Textile Science**

Future research on visual-tactile correlation models should focus on developing mathematical models that predict tactile characteristics based on visual cues. Including additional sensory attributes such as softness and elasticity can refine these models. Current methods often lack the complexity needed to accurately reflect the relationship between visual and tactile perceptions, which would lead to inadequate assessments of fabric handfeel. By employing advanced image processing and machine learning algorithms, researchers can enhance the accuracy of these models, which would make them more effective for applications like virtual fitting and online textile commerce.

- **Advanced Pore Structure Analysis in Nonwoven Fabrics**

Using advanced image processing techniques, such as computed tomography and high-resolution microscopy, can provide direct and accurate assessments of pore structures in spunlace textiles. This approach enhances understanding of how pore configurations affect textile properties, which would overcome the limitations of indirect assessments. Exploring the relationship between pore structures and properties like thermal and air permeability can improve fabric wear comfort and performance. Applying ANNs to analyze and optimize these characteristics can lead to significant advancements in textile engineering, thus resulting in next-generation textiles with tailored attributes for specific applications.

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