Opportunities for AI-assisted Process Control in Textile Wet Processing

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Abstract
Textile wet processing, i.e., desizing and bleaching, dyeing, printing, and finishing, is one of the most complex and resource-consuming stages in textile production. The processes involve multiple parameters, such as temperature, rate of rise in temperature, pH, chemical concentration, bath liquor ratio, and time, which must be controlled precisely to achieve consistent and desired product quality. Traditional process control relies largely on manual supervision and conventional automation systems, often leading to process variations, increased resource consumption, and inconsistent quality. Artificial Intelligence (AI) offers significant opportunities to enhance process control by enabling predictive modelling, real-time monitoring, and intelligent decision support. This paper examines the potential applications of AI in textile wet processing, with a focus on process optimisation, defect prediction, resource efficiency, and smart manufacturing. The paper highlights the technological framework, implementation opportunities, and challenges associated with integrating AI-assisted systems in textile wet processing industries.

Keywords
Artificial Intelligence, Textile Wet Processing, Process Control, Machine Learning, intillegent Manufacturing, Industry 4.0

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1.0 Introduction:

Textile wet processing consists of a sequence of chemical treatments applied to textile materials to improve appearance, finish, durability, and functionality. These processes include desizing, scouring, bleaching, dyeing, printing, and finishing. To maintain consistent and right first-time product quality in these operations, a strict control of multiple process parameters is required.

As per our experience during various studies at textile process houses' shop floor, the traditional process control systems in textile dyeing and finishing are often based on predefined recipes and operator experience. However, variations in raw materials, machine process conditions, and environmental factors frequently lead to deviations in product quality.

Artificial Intelligence (AI) is a branch of computer science dedicated to the study of computational activities that require intelligence when performed by humans. "Intelligence" is the computational part of the ability to achieve goals [1]. Recent developments in deep neural networks and distributed IoT architectures [2], a part of Artificial Intelligence (AI), have emerged as a transformative technology capable of enhancing automation and decision-making in industrial processes. AI techniques like machine learning, neural networks, and deep learning can analyse large datasets of the process and identify patterns that enable predictive and adaptive control systems. The integration of AI with IoT sensors, data analytics, and automation systems can significantly improve the efficiency and reliability of textile wet processing operations.

2.0 Overview of textile wet processing

Textile wet processing involves chemical and mechanical treatments generally applied in aqueous media. The main processes are shown in the table below:

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Process	Purpose
Desizing	Removal of size materials from fabric
Scouring	Removal of natural impurities and oils
Bleaching	Improving whiteness of fabric
Dyeing	Imparting color to textile materials
Printing	Creating patterns/designs on fabric
Finishing	Enhancing/imparting functional properties

These processes require precise control of variables such as:

- Temperature and its rate of rise as per the process requirement
- Time
- pH level
- Chemical dosage
- Bath Liquor ratio
- Mechanical agitation/actions
- Tension on the material during the process

Small variations in these parameters may lead to quality issues or fabric damages, such as uneven dyeing, poor shade reproducibility, strength loss, improper appearance, roughness, extra softness, etc.

3.0 Artificial Intelligence in Process Control

Artificial Intelligence (AI) is a branch of computer science dedicated to the study of computational activities that require intelligence when performed by humans. "Intelligence" is the computational part of the ability to achieve goals [1]. Thus, Artificial Intelligence refers to computational techniques that allow machines to perform tasks that typically require human brain smartness. In textile processing, AI techniques include:

- Machine Learning (ML)
- Artificial Neural Networks (ANN)
- Deep Learning
- Reinforcement Learning
- Computer Vision
- Predictive Analytics

AI systems can process large volumes of production data (previous history as well as current lot data) and generate optimized process parameters automatically by utilizing above mentioned aspects of AI.

For example, machine learning models can analyse historical production data to predict the optimal dyeing conditions required to achieve a specific shade with minimal chemicals for the current lot under process..

4.0 Opportunities in textile wet processing

As we know, there are several stages and operations in textile wet processing. Among these critical steps, those deciding the product quality shall be considered for the AI integration. To achieve the AI-assisted process outcome, we need to have certain changes or additional features available in the machine under consideration. The features are like the provision of various sensors, flow meters, data processing systems, etc.

Some of the processes where AI can be implemented are given below;

4.1 Intelligent Dyeing Process Control

Dyeing is one of the most critical wet processing operations, which is affected by variations in input colour chemicals, fabric or yarn under dyeing, and other process conditions . AI can optimise dyeing process parameters by analysing process data and predicting results. Artificial Intelligence (AI) enables the transformation of conventional dyeing into an intelligent, self-correcting system through real-time monitoring, prediction, and control.

The AI applications in this dyeing process can be used as follows;

- Automated dye recipe optimisation by considering exhaustion curves of individual dyes
- Salt and soda dosing
- Time duration adjustment as per the shade output desired
- Real-time shade prediction
- Dye uptake and buildup monitoring
- Reduction of re-dyeing operations

Machine learning algorithms can modify temperature and its ramping, pH levels, colour concentration and hold time to achieve consistent shade results.

4.2 Predictive Quality Control

Predictive Quality Control (PQC) is an advanced approach that uses Artificial Intelligence (AI) and data analytics to predict quality outcomes before defects occur. Predictive Quality Control (PQC) refers to the advance detection and prevention of quality issues before they occurs[5]

Key applications are:

- Prediction of shade variation and patchy dyeing
- Detection of process abnormalities
- Real-time monitoring of dye bath conditions

AI-based inspection systems using computer vision can detect defects such as stains, misprints, and uneven colouration with high accuracy, improving overall product quality. The working principle involves steps like;

Data collection Data processing Model training prediction corrective action during the process itself

An example of predictive quality control for shade matching is explained below.

Suppose AI predicts that the shade deviataion $\Delta E > 1.2$, then the system takes actions like increasing dye-uptake time and or adjusts temperature curve and or modifies the bath pH. Thus, the final output will be the correct shade and no reprocessing

4.3 Chemical Consumption Optimisation

AI algorithms can analyse historical dyeing recipes and process results to determine the most efficient chemical usage.

Benefits include:

- Reduced chemical consumption
- Improved dye fixation
- Lower processing costs

By analysing process data, AI systems can recommend optimal chemical dosage levels for different fabric types.

The below table illustrates the difference between the conventional and AI-based approaches [6].

Aspect	Conventional Method	AI-Based Optimization
Defect detection speed	Moderate	High
Precision	Medium very high	Very High
Dosing	Fixed recipes	Dynamic dosing
Control	Operator-based	Data-driven
Accuracy	Moderate	High
Waste	High	Low
Scalability	Limited	Easily scalable

The working principle involves steps like
Data collection Data processing Model training prediction dosage optimisation and execution of chemical dosing

The possible application areas are listed as

- Dyeing process, i.e. salt and soda dosing
- Improve dye fixation
- Control H_2O_2 dosage in bleaching to avoid fabric damage and whiteness variation
- In scouring alkali concentration optimisation
- Optimise chemical dosing in ETP so that sludge generation is reduced.

For example, in conventional dyeing as we have observed that we are using 80 gpl salt for dark shades, then in the AI-assisted process, the same shade may be obtained with 60-70 gpl salt concentration. Thus, ultimately, effluent TDS and sludge generation are reduced. .

4.4. Energy and Water Efficiency

Textile wet processing is highly resource-intensive, consuming large amounts of water for washing and rinsing activities, and energy is used for heating, drying, and pumping purposes. Now, it is the time demand that we should seek and invest in water and energy efficient circular solutions to increase compitativeness and sustainability [7].

AI-based energy management systems can:

- Monitor energy consumption in real time.
- Predict energy demand for production schedules.
- Optimise steam and water usage, avoiding excessive utility usage.

Such systems can significantly reduce energy consumption and improve sustainability in textile processing.

An AI-based system can optimise water usage through Smart liquor ratio control, optimised rinsing cycles, Water reuse and recycling, and leak detection, etc.

Whereas, AI-based energy optimisation is done through temperature optimisation, steam consumption reduction, machine load optimisation by reducing idle time, and predictive maintenance, which detects inefficiencies in motors and pumps to save further energy.

4.5 Predictive Maintenance of Processing Machines

Based on various intractions and studies conducted by BTRA mumbai in textile industry, it was seen that machine downtime due to unexpected breakdowns and hence utilisation loss, shade variation, delivery delays and increased maintenance costs, etc., are major challenges in textile processing plants.

AI-enabled predictive maintenance can:

- Monitor machine parameters
- Predict potential equipment failures.
- Schedule maintenance before breakdowns occur

This improves machine availability and reduces production losses. While implementing an AI system for this, one should consider mechanical components (Valves, Bearings, Pumps, Heat exchangers), electrical components (motors, drives, and control panels),and process components(temperature controller system, pressure system and flow system)

Mechanical data (vibration signals, noise levels, rotation speed), thermal data (motor and bearing temperatures) , electrical data (current, voltage and power consumption) and process data (flow rate, pressure and temperature stability) are important inputs for machine learning, sensor data analysis and pattern recognition.

The prediction for pump failure, motor health monitoring, heat exchanger efficiency, valve malfunctioning detection, etc., can be done by this AI assisted system.

4.6 Digital Twin and Smart Process Simulation

A Digital Twin is a real-time virtual replica of a physical textile process (such as dyeing, bleaching, or finishing). It continuously receives live data from machines through sensors and simulates the exact behaviour of the process using AI and mathematical models[8].

AI can simulate:

- Dyeing /processing cycles
- Chemical reactions modelling
- Fabric behaviour during processing
- Process faults

This allows engineers to optimise processes before an actual production begins.

Practical Example (Soft Flow Dyeing Machine) :-

Digital Twin can:

- Simulate the full dyeing cycle before execution.
- Predict final shade accuracy (ΔE value)
- Optimize:
  - Heating rate
  - Chemical dosing sequence
- Detect:
  - Risk of uneven dyeing

5.0 Framework and requirements for AI-Assisted Wet Processing

The implementation of AI-assisted process control requires integration of several technologies and tools, which include process knowledge, data infrastructure, machine connectivity, and intelligent algorithms. The objective is to transform conventional wet processing into a data-driven, automated, and self-training optimising system.

The key components required in AI implementation in a textile process house are listed as below;

A. Sensors and Data Acquisition
   a. Temperature sensors
   b. pH sensors
   c. flow meters
   d. spectrophotometers
   e. Pressure sensors
   f. Speed sensors
   g. Load cells – fabric weight

B. Machine signals
   a. Pump status
   b. Valve positions
   c. Machine speed

C. Industrial IoT Platform
   a. Machine connectivity
   b. real-time data collection/acquisition

D. Data Processing Layer
   a. machine learning algorithms
   b. recipe database
   c. historical batch data
   d. cloud database
   e. predictive models

E. Control System Integration
   a. PLC/SCADA systems
   b. automatic parameter adjustment

F. AI & Analytics Layer
   a. machine learning models
   b. Neural network
   c. Predictive analytics
   d. predictive models

G. User Interface
   a. dashboards for operators
   b. decision support systems

6.0 Benefits of AI-assisted wet processing:-

The AI implantation benefits are tabulated below.

Benefit	Impact
Improved shade reproducibility	Better product quality
Reduced chemical consumption	Lower production cost
Reduced water usage	Environmental sustainability
Energy optimization	Lower operating costs
Predictive maintenance	Reduced machine downtime

Studies have shown that AI-based monitoring and defect detection systems can achieve accuracy levels above 97% and significantly reduce material waste in textile manufacturing [3,4].

7.0 Challenges in implementation

Despite the potential benefits, several challenges exist in adopting AI in textile wet processing, which are listed as below.

a) Lack of structured process data or inconsistent data

b) High initial investment in sensors and digital infrastructure

c) Need for skilled personnel/engineers in data analytics.

d) Integration issues with conventional or old- type machines

e) Compatibility with control systems

f) Retrofitting challenges

g) Data security and system reliability concerns

Addressing these challenges requires coordination between textile process engineers, data scientists, and equipment manufacturers.

8.0 Future prospectus .

The future of textile wet processing is in Industry 4.0 and intelligant production systems. AI will play a central role in transforming conventional textile plants into intelligent production systems or units.

Future developments may include:

- Fully autonomous dyeing plants
- AI-based colour matching systems and fabric handfeel assessment
- Self-learning process optimization models
- AI-integrated sustainability monitoring

With advancements in IoT, cloud computing, and data analytics, it is expected that AI-assisted textile processing will become more accessible to small and medium-sized textile enterprises.

9.0 Conclusion

Artificial Intelligence provides large opportunities for improving process control in textile wet processing. By integrating AI with sensors, automation units, and data analytics softwares, textile processors can achieve enhanced process stability and assurance, improved product quality, and decreased operating costs. AI-assisted process control enables predictive decision-taking , real-time monitoring, and optimised resource utilisation. This will make textile processing more efficient and sustainable. As Industry 4.0 technologies continue to evolve, AI will become a key component for intelligent textile production systems.

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