

# Digital and Sustainable Transition in Textile Industry through Internet of Things Technologies: A Pakistani Case Study

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**Abstract:** The textile industry, a vital contributor to Pakistan’s economy, faces pressing challenges in transitioning towards sustainability amid global environmental concerns. This manuscript presents a comprehensive case study on the implementation of IoT-driven strategies in the Pakistani textile sector to achieve digital and sustainable transformation. The findings reveal that the implementation of IoT technologies facilitated real-time environmental monitoring, enabling compliance with regulatory standards, and fostering sustainable manufacturing practices. Ultimately, this manuscript offers valuable insights into the transformative potential of IoT technologies in driving sustainable practices in the textile industry. The case study serves as a benchmark for other textile-producing regions aiming to embark on a digital and sustainable journey. These findings hold significant implications for the ongoing dialogue on sustainable industrial development, providing valuable direction for policymakers and stakeholders in shaping a more resilient and ecologically conscious future. Future research should prioritize addressing issues like data confidentiality and interoperability while adhering to standard requirements. Additionally, exploring analytics and machine learning methods for predictive maintenance, optimized performance, and operational improvement is crucial.

**Keywords:** sustainability; digitalization; innovation; IoT (Internet of Things); SDGs (sustainable development goals)

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## 1. Introduction

The textile industry employs over 60 million people in the Asian garment sector, as reported by the International Labor Organization (ILO) [1]. In Pakistan, the textile industry is a vital sector of the economy. According to the Pakistan Bureau of Statistics, the textile sector contributes approximately 8.5% to the country’s GDP [2]. This industry is a major source of employment, providing livelihoods to over 40% of the industrial workforce in Pakistan, as reported by the State Bank of Pakistan [3]. Pakistan’s textile exports amounted to USD 31.782 billion in the fiscal year 2021–2022, making it one of the largest export earners for the country, according to data from the Ministry of Commerce, Government of Pakistan [4]. The IoT promises to reshape the textile industry by enhancing efficiency, productivity, sustainability, and customer experiences [5]. It facilitates the improved acquisition of object information, cost reduction, and waste minimization, laying the groundwork for transformative changes in textile manufacturing [6]. Smart manufacturing in the textile industry embraces digital transducers enabled by IoT technologies, but proper deployment alongside remote sensing and IoT energy concepts is crucial for enhancing production efficiency and sustainability [7,8]. The application of IoT technology in the textile sector underscores the significance of digitization and sustainability, particularly in monitoring and managing ecological environments [9]. The

textile industry, despite its economic significance, faces environmental challenges due to resource-intensive and polluting processes [10]. IoT-based monitoring responds to the need for easy networking, real-time and adaptive monitoring, and efficient data exchange, addressing the limitations of manual measurements and outdated systems. However, there is a gap in utilizing innovative strategies to induce flexibility, security, energy efficiency, and comprehensive performance parameters in smart manufacturing systems for the textile sector [11]. This research aims to bridge the gap by developing a framework that integrates software and hardware infrastructure with secure data transmission. Emphasizing real-time monitoring and preventive measures for ecological events, this initiative seeks to effectively manage and reduce environmental threats. Key motivations include increasing efficiency, reducing waste, and enabling better decision-making. Additionally, smart manufacturing leverages digital technologies, IoT devices, and data analytics to create interconnected and adaptive production systems, optimizing resource allocation (such as raw materials and energy usage), reducing energy consumption, mitigating waste generation (including solid waste, wastewater, and emissions), enhancing supply chain transparency, and advancing environmental monitoring protocols (including air and water quality monitoring) to promote sustainability goals within Pakistan's textile industry. While previous studies have explored these technologies in various sectors, there is a lack of understanding regarding their implementation in textiles, especially in terms of scalability, interoperability, and data security. The novelty of this research lies in its focus on implementing IoT-driven strategies tailored specifically to the Pakistani textile sector to achieve digital and sustainable transformations. This industry-specific approach distinguishes research from broader studies on IoT implementation by providing tailored solutions for challenges like device integration, decision-making, and scalability while exploring opportunities such as advanced sensors, AI integration, and blockchain for traceability. A comprehensive examination of merging IoT with remote sensing addresses previous research gaps and provides insights specific to the textile industry. Additionally, challenges unique to this sector are identified and tackled, offering practical solutions to enhance operational efficiency, contribute to sustainability objectives, and ensure customer satisfaction, thereby driving innovation and competitiveness. The planned methodology involves analyzing various physical parameters remotely sensed using a wireless sensor network and displaying the data on a GUI. Real-time data from multiple distant locations are transmitted through a serial link and plotted on the GUI, facilitated by collaboration at the infrastructure level to improve energy efficiency but lacking consistency for the long-term and continued improved production [12]. Stakeholders, including public users, data scientists, and government agencies, can benefit from IoT-based monitoring systems. This research provides insights into trends, opportunities, and challenges in integrated networks for the textile domain, although large-scale implementation may pose challenges for small- or medium-sized firms. Collaboration with developers of communication modules and monitoring platforms is crucial for enhancing these systems. Integrating digitalization and sustainability concepts into IoT infrastructure can enhance the monitoring and supervision of ecological environments. The rest of the manuscript is organized as follows: Section 2 explores the literature on IoT integration with remote sensing and analyzes barriers to smart manufacturing implementation. Section 3 presents material and method outlines, followed by Section 4 on results. Section 5 discusses potential applications, challenges, practical implementation strategies, and future research directions. Conclusions are summarized in Section 6.

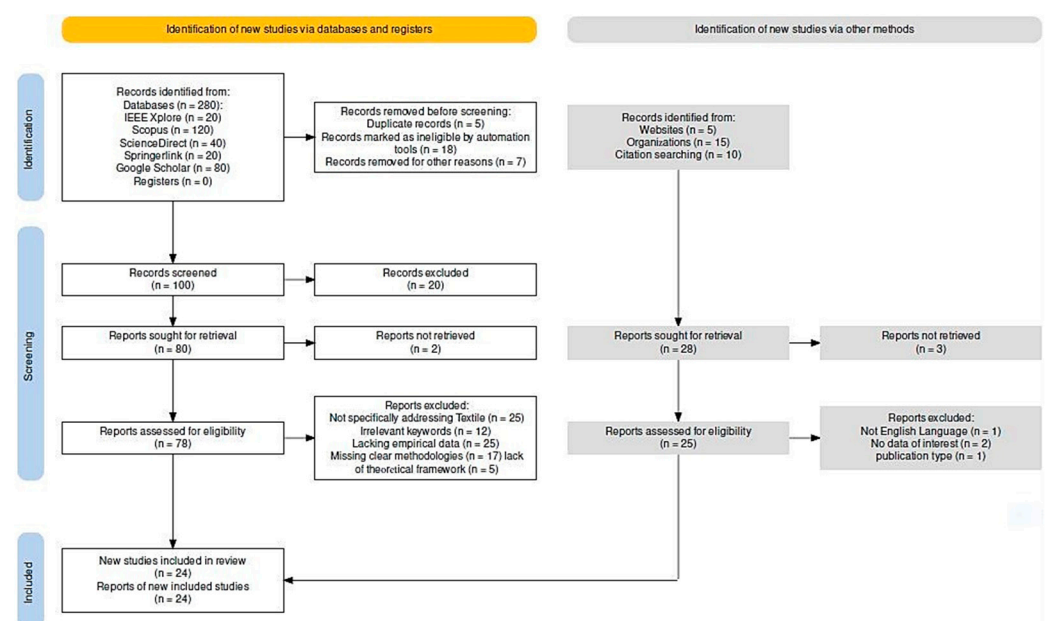
## 2. The Literature Review

The literature review analyzed the articles based on their coverage of IoT (Internet of Things) applications, with an emphasis on remote sensing and its benefits, exploration of innovative frameworks and systems, advancements in real-time quality monitoring and predictive analysis, and a focus on specific aspects of defect detection, quality assurance,

and fault diagnosis. The collective findings from these studies highlighted the growing interest in integrating IoT with remote sensing techniques in the textile industry and emphasized the potential for improved efficiency and quality control. However, the review also identified the need for further research to address challenges related to data integration, security, and scalability in implementing IoT and remote sensing systems in this industry. Several articles were identified that contributed to the state of the art in this field, and their analysis is mentioned in Figure 1. The literature review highlights gaps in comprehensive solutions for IoT implementation, particularly in Industry 4.0 initiatives, due to challenges like cybersecurity and interoperability in this sector. Existing research lacks practical frameworks addressing data security, data integration, device interconnection, timely decision-making, scalability, and deployment strategies effectively. The digital and sustainable transition in the textile industry through IoT technologies and remote sensing of physical parameters is a global trend, as evidenced by research in various countries. The textile industry in Pakistan, a key contributor to the nation's economy, is grappling with the imperative to transition towards more sustainable and digitalized practices [13]. The emergence of Industry 4.0 and the proliferation of Internet of Things (IoT) technologies offer promising avenues to address the industry's environmental impact and operational inefficiencies [14]. A review of the existing literature reveals several critical challenges and opportunities in this domain [15]. The textile industry, though not considered energy-intensive, collectively consumes a significant amount of energy and water, and produces substantial pollution [13]. The integration of IoT technologies can further enhance the textile industry's sustainability and digital transformation. IoT and its associated smart manufacturing solutions can optimize resource utilization, streamline production processes, and enable real-time monitoring and control of environmental parameters [14]. As evidenced in the literature, policy interventions and a holistic approach to sustainable practices are crucial to driving the necessary changes within the Pakistani textile industry. Studies highlight the integration of IoT, RFID, and sensors in the textile supply chain to enhance sustainability, data-driven decision-making, and traceability [16]. Furthermore, Tanaka et al. introduce a wireless multi-point temperature sensor system for machine tools, enabling a robust estimation of thermal displacement [17]. By measuring temperatures at multiple points and utilizing Finite Element Analysis (FEA), this study achieves an accurate estimation of thermal errors and their impact on the volumetric error model. This research aligns with previous papers by emphasizing technological advancements and their relevance in optimizing machine tool performance within the framework of Industry 4.0. Olhan et al.'s study complements the use of IoT in textile manufacturing by investigating the effect of machining processes and fiber architectures on textile fiber-reinforced structural composites. By analyzing the machine's hole behavior, bearing strength, and failure mechanisms, it provides valuable insights for optimizing composite manufacturing through IoT-driven monitoring and control [18]. Additionally, Angelucci et al. present a review article that examines the integration of textile technologies and sensor-based garments for continuous monitoring of physiological parameters [19]. This study aligns with previous research by emphasizing the importance of advanced materials, manufacturing processes, and technical solutions to ensure both functionality and comfort in sensor-based garments used for physiological monitoring. The study by Zahid et al. expands upon the existing research by investigating textile-based smart sensors, particularly Intrinsically Conductive Polymers (ICPs) and Elastomeric Conductive Polymers (ECPs), which offer mechanical adaptability to textile fabric [20]. These sensors provide lightweight, stretchable, and wearable properties, making them suitable for real-time and online monitoring of human health. The study aims to discuss recent developments in smart monitoring sensors, linking them to broader research on integrating textile technologies and sensorized garments for continuous physiological monitoring. Ayora et al. focused on how machine learning and neural networks offer efficient control and awareness of quality, enabling energy savings of up to 20% per

machine [21]. Integrated sensors and real-time monitoring facilitate process parameter optimization for low energy consumption and high quality, empowering machine operators and production management with real-time information for improved decision-making and digital transformation. Several studies highlight the growing importance of sustainability considerations in the textile sector due to increasing environmental awareness and regulatory pressures. Chevrollier et al. explore how dynamic capabilities, such as sensing and seizing, can support sustainable strategic orientations in the apparel industry [22]. In line with the proposed topic, Xu et al. presented an article that combines UAV (Unmanned Aerial Vehicle) multispectral and RGB (Red, Green, Blue) remote sensing and machine learning to model cotton fiber quality indicators, achieving improved prediction accuracy compared to traditional methods [23]. It provides a non-invasive and scalable approach for predicting cotton fiber quality, aiding variety breeding and commercial decision-making in the industry. Further advancements have been made in real-time quality monitoring and predictive analysis. Nouinou et al. examine the impact of Industry 4.0 technologies on decision-making in the textile and clothing industry, highlighting trends such as data-driven, real-time, decentralized, integrated, and sustainable decision-making [24]. Dal Forno et al. considered the systematic literature review that explores the development process of Industry 4.0 in the textile and apparel sector, highlighting concepts and examples related to IoT, cloud computing, big data, 3D printing, augmented reality, and more [25]. A dynamic knowledge modeling and fusion method based on a knowledge graph is proposed by Shen et al. for custom apparel production, addressing the challenges of data redundancy and weak correlations [26]. Their method enables effective knowledge fusion and representation, demonstrated through a case study on suit production in a custom apparel factory to enhance efficiency and quality control. The integration of IoT and remote sensing enables real-time monitoring and analysis of physical parameters, leading to improved process control, reduced waste, and enhanced product quality. The implementation of IoT in circular textile economy practices is crucial for promoting sustainability, resource efficiency, and real-time traceability throughout the textile value chain [27]. While the textile industry faces challenges in adopting smart manufacturing technologies, case studies demonstrate successful transitions to smart processes through IoT applications like RFID technology for material tracking and custom product manufacturing [28]. The implementation of real-time monitoring using IoT sensors in the Pakistani textile sector can significantly enhance operational efficiency and sustainability [29]. Current practices involve utilizing RFID technology for improved inventory management, product traceability, and enhanced customer connectivity in the apparel industry [30]. Challenges in implementing real-time monitoring with IoT sensors include the complexity of global networks and technological integration difficulties in the apparel sector [31]. The use of IoT sensors in real-time monitoring positively impacts sustainability practices by enabling more efficient controls, traceability in the value chain, and economic benefits in the apparel industry [32]. Potential benefits of using IoT sensors for real-time monitoring include asset visibility, risk management, and loss mitigation, while limitations involve addressing technological integration challenges and ensuring data privacy and sustainability concerns are balanced [33]. The literature review was conducted using databases such as Scopus, IEEE Xplore, ScienceDirect, Springer, and Google Scholar. A total of 280 articles were initially identified. The process of selecting and analyzing relevant research for our study involved a methodical approach aimed at aligning with our research focus and objectives. Initially, we determined keywords and phrases that encapsulated various sides of IoT applications, remote sensing benefits, Industry 4.0 challenges, and quality monitoring specific to the textile industry. These keywords underwent an iterative refinement process, starting with broad terms such as “digital transition”, “textile industry”, “IoT technologies”, and “Pakistani textile”, which were then polished down to more specific terms like “digitalization of textile manufacturing”, “sustainable practices in the textile industry”, “IoT applications in textile production”, “smart textile manufacturing solutions”, and “remote sensing implementation in Pakistani textile.” The selection

of these keywords was based on their relevance to our research topic and study objectives. We consulted subject matter experts, reviewed the existing literature, and considered established terminology in the field to identify inclusive terms. Utilizing Scopus's Boolean syntax, we merged expressions like "(TITLE-ABS-KEY (digital transition) AND TITLE-ABS-KEY (textile industry))" and "(TITLE-ABS-KEY (IoT technologies) AND TITLE-ABS-KEY (Pakistani textile))" to refine search queries and retrieve more relevant results, leveraging operators like AND, NOT, and OR to enhance result relevance. Following a rigorous screening process, 78 papers were deemed eligible for inclusion, while others were excluded due to reasons such as not specifically addressing the textile industry, irrelevant keywords, lacking empirical data, and a lack of theoretical framework as mentioned in Figure 1. Additional studies were incorporated using different methods, resulting in the inclusion of 24 more articles, while those not meeting the criteria were excluded due to reasons such as not being in English, lack of data of interest, and publication type.



**Figure 1.** Selection and analysis of relevant research.

### 2.1. Barriers to IoT Implementation in Textile Industry

Implementing IoT technologies in various sectors, including the textile industry, faces numerous barriers that hinder their seamless integration and efficacy. One significant limitation is the lack of cybersecurity measures, which pose a threat to the integrity and safety of data collected from IoT devices. The absence of a comprehensive framework for IoT deployment further exacerbates these challenges, leading to interoperability concerns among sensor networks and difficulties in data integration [34]. Financial constraints also play a crucial role, as many enterprises lack the necessary financial capabilities to invest in IoT infrastructure and training [35]. Additionally, the rapid growth of expenditures and the need to master new industrial products create financial barriers, making it difficult for companies to adopt these technologies [36]. The complexity of sensor networks requires valid models for practical implementation, flexibility in adaptation, and the development of more comprehensive models to support complex computations [37]. Furthermore, issues related to hardware and software integration, safety management, and stability barriers add to the challenges, limiting the deployment capabilities of IoT systems [38]. The potential for information leakage and cyberattacks on IoT-enabled infrastructure highlights the necessity for robust cybersecurity measures and self-healing mechanisms in case of device failures [39]. Additionally, there is a significant need for data fusion technologies and the reduction of energy costs across all sectors to enhance the

efficiency and sustainability of IoT systems [40]. The lack of skilled workers, insufficient knowledge about construction materials, and inadequate planning further impede the effective implementation of IoT technologies [41]. Moreover, cultural barriers, lack of automation, and privacy issues contribute to the resistance against adopting IoT solutions, while the limited availability of IP addresses and the proliferation of incompatible standards hinder the integration of different sensors and networking gadgets [42]. Lastly, the absence of qualitative interviews, insufficient communication, and lack of comprehensive data collection create gaps in the information available to decision-makers, making it challenging to develop effective IoT strategies [43]. Addressing these multifaceted challenges requires a holistic approach that encompasses technical, financial, organizational, and cultural dimensions to facilitate the successful implementation of IoT technologies in the textile industry and beyond. The integration of advanced technologies in textile manufacturing harnesses real-time data analytics, predictive maintenance, and adaptive process control to boost operational efficiency and minimize waste. This holistic approach aims to revolutionize traditional manufacturing methods, making them more agile, responsive, and sustainable. By driving continuous improvement and meeting evolving customer needs while also prioritizing environmental sustainability and social responsibility, this transformation enhances competitiveness and ensures long-term success. Addressing these obstacles is crucial for unlocking the full potential of the integration of smart manufacturing systems with IoT technologies. Thus, this research will investigate how real-time monitoring using IoT sensors contributes to enhancing the operational efficiency and sustainability of the Pakistani textile sector. It investigates the critical challenges and practical implementation strategies associated with deploying IoT and remote sensing technologies in the textile industry of Pakistan. Further, it examines the specific applications and benefits of merging IoT with remote sensing technologies in the context of Pakistani textile manufacturing and how these technologies contribute to sustainability goals. It presents a case study on the implementation of an IoT-driven framework in the Pakistani textile sector to serve as a benchmark for other textile-producing regions aiming for digital and sustainable transformations. The methodology employed for selecting articles for inclusion in Table A1 (Appendix A) was conducted rigorously to ensure comprehensive coverage of research pertaining to the integration of IoT and remote sensing in the Pakistani textile industry, along with the associated limitations in its implementation within the prevailing economic conditions. Selected articles were assessed for quality and relevance by evaluating their methodology, findings, and limitations related to IoT barriers, which included various aspects such as cybersecurity issues, financial constraints, lack of frameworks, integration challenges, frameworks for IoT, optimized management systems with data-based automation and complex data analytics strategies, investment issues and cost reduction, power consumption, social and environmental aspects, and the business view of IoT. Articles with robust methodologies and a clear identification of barriers were prioritized. The systematic analysis of research gaps was conducted using two primary tables: Tables A1 and A2. The identified barriers were categorized to highlight recurring themes and common challenges across different studies. This categorization helped in understanding the prevalent issues in IoT implementation and provided a comprehensive view of the barriers. In Table A2, mapping was performed based on the primary focus and contributions of each study. By analyzing the distribution of studies across these focused areas, research gaps were identified. Areas with fewer studies or limited exploration were flagged as significant gaps. For instance, while there were numerous studies on Industry 4.0 and smart manufacturing, areas like framework development for IoT and human factors/social impact had fewer contributions. The analysis involved looking at overlaps in research findings to confirm well-established barriers and identify underexplored areas that require further investigation. This provided a clear picture of where existing research is concentrated and where additional studies are needed.

## 2.2. Research Gap: Exploring the Integration of IoT in the Textile Industry for Improved Productivity and Sustainability

In exploring the integration of IoT within the textile industry to enhance productivity and sustainability under the umbrella of Industry 4.0, several key areas merit attention. First, while there is ample evidence supporting the potential of the Internet of Things (IoT) to revolutionize various sectors, including textiles [44], there is a growing complexity associated with its adoption. Challenges such as cybersecurity vulnerabilities, a lack of infrastructural support, financial constraints, limited knowledge about construction materials, and escalating expenditures pose significant hurdles [45]. The research aims to confront these challenges head-on by adopting a comprehensive approach, from concept inception to final implementation, to address the multifaceted issues hindering seamless integration. By leveraging structured information and proven strategies, organizations can navigate through these complexities and streamline their processes effectively [46]. To delve deeper into the potential of IoT integration and address the identified research gap, our study will explore the specific contributions of real-time monitoring using IoT sensors to operational efficiency and sustainability in the Pakistani textile sector. Therefore, this study proposes the following research questions:

Research Question 1: How does real-time monitoring using IoT sensors impact operational efficiency and sustainability in the Pakistani textile sector, focusing on variables such as machinery breakdowns, energy consumption, and water usage?

Research Question 2: What are the specific applications and benefits of merging IoT with remote sensing technologies in Pakistani textile manufacturing, focusing on variables such as quality control measures, waste reduction, cost reduction, process optimization, resource efficiency (energy, water), and product traceability, and how do these technologies contribute to sustainability goals?

Research Question 3: What are the critical challenges and practical implementation strategies associated with deploying IoT and remote sensing technologies in the textile industry of Pakistan, focusing on variables such as technical barriers, regulatory constraints, and practical implementation strategies?

Furthermore, the study underscores the importance of adopting a knowledge management approach to capture, organize, and disseminate successful practices within organizations. This approach facilitates informed decision-making and the implementation of effective strategies to ensure product quality and operational efficiency [47]. This research aims to bridge this gap by providing insights into the integration of IoT and remote sensing in the textile industry, with a focus on enhancing production efficiency and sustainability. The findings presented in Table A2 (Appendix A) serve to illuminate this gap and offer a pathway toward achieving enhanced efficiency in textile production through IoT and remote sensing integration.

## 3. Materials and Methods

Our research focuses on a case study conducted at a medium-sized textile manufacturing company located in Faisalabad, Pakistan, which is a major hub for the country's textile industry. This location was chosen due to its significant contribution to Pakistan's economy and the pressing need for sustainable practices in this sector. The company was selected based on its openness to integrating IoT technologies and its representation of typical operational and environmental challenges faced by the industry. The case study's context includes the company's size, employing around 350 workers and 50 machines and producing a variety of textile products, including clothing, sheets, bags, and baskets. This context is crucial for understanding the operational factors and challenges, such as energy consumption, surveillance, environmental impact, and quality control requirements, that necessitate IoT-driven solutions. The study's findings, while specific to this company, offer insights that are both unique and generalizable, providing a blueprint for other textile manufacturers aiming to achieve digitalization and sustainability. The flowchart in Figure

2 outlines a structured approach for IoT research in the textile industry, covering key steps from the literature review to future directions and conclusions.

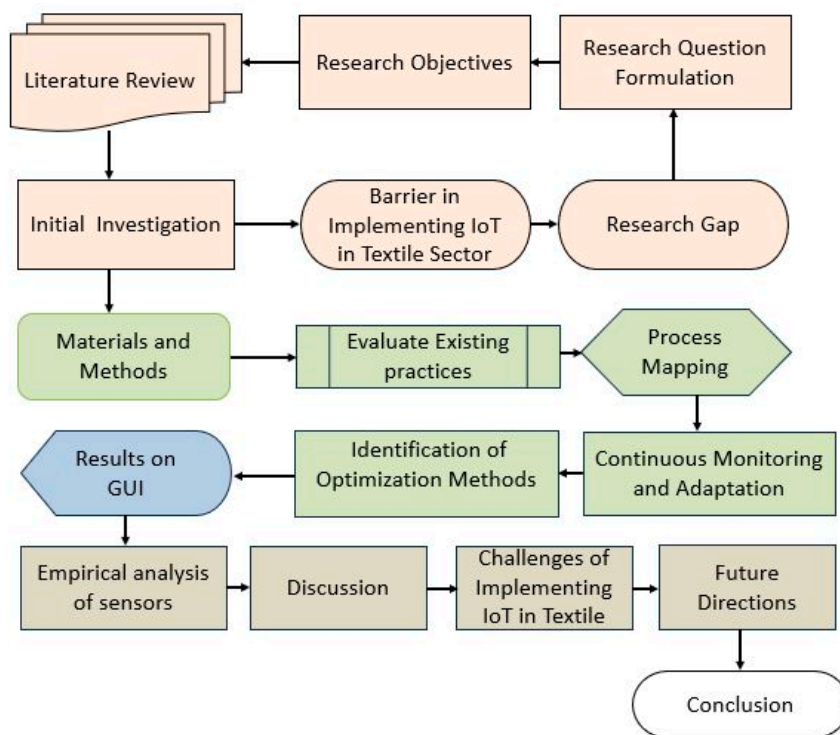


Figure 2. Structured research methodology for IoT implementation in textile sector.

The methodology employed in this pilot study aimed to showcase the feasibility of implementing a structured framework for real-time monitoring in Pakistan’s textile sector using an integrated approach of smart sensors, as illustrated in Figure 3. Technical assistance, either virtual or physical, was provided to ensure the interconnection of these sensors.

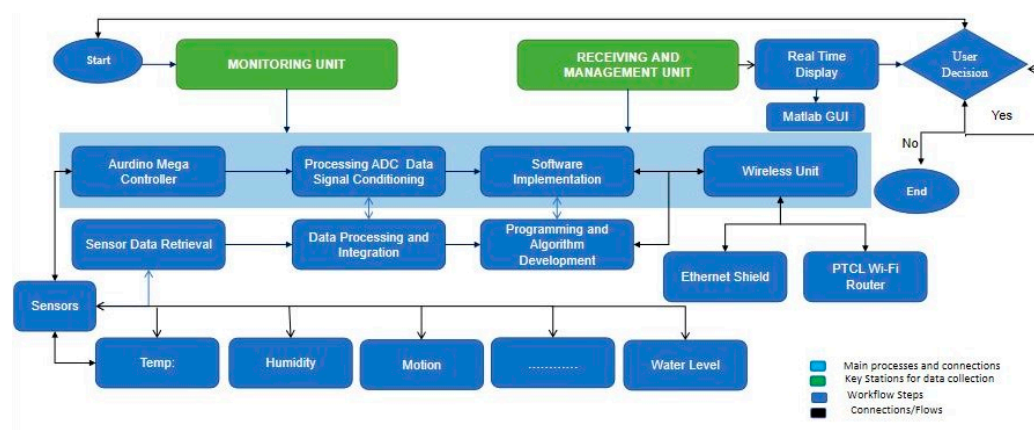


Figure 3. A flow chart paving the way to a smart system transformation.

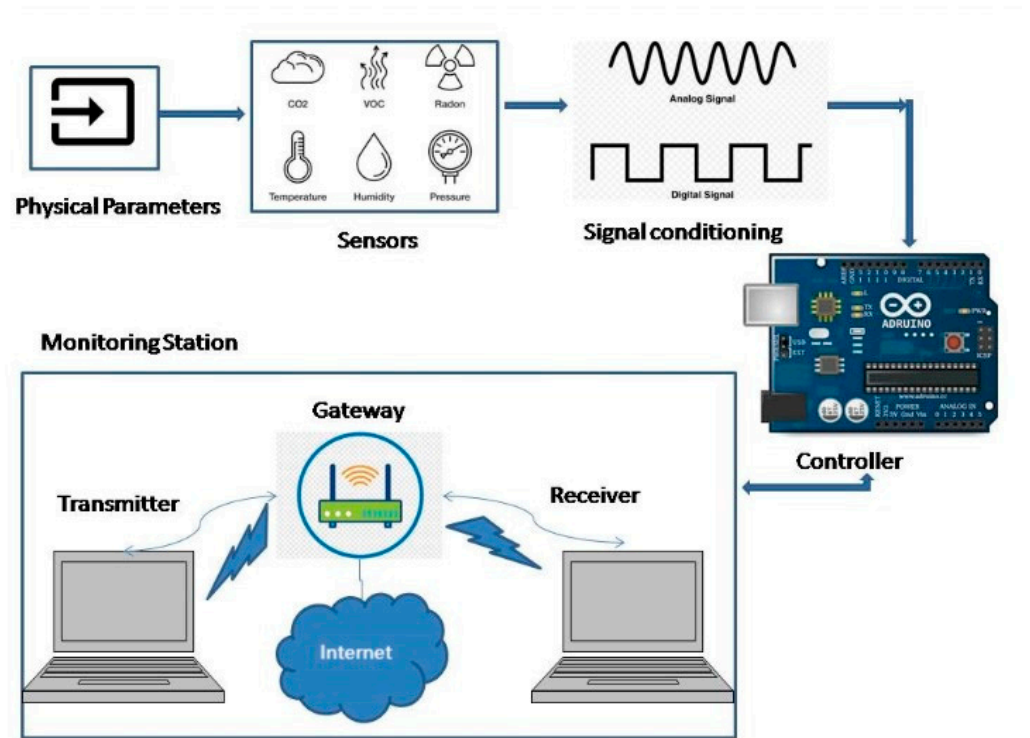
Drawing upon previous research highlighting the need for improved implementation of IoT models [48], this study emphasized the importance of data analytics and decentralization in establishing a successful and secure IoT network [49]. This case study is highly relevant to the Pakistani textile industry because it addresses the sector’s unique needs and requirements, such as increased efficiency, quality monitoring, cost savings, transparency, and traceability, all of which support the sustainability objectives covered



in detail in the paper's application and benefits section. Pakistani textile companies may acquire a competitive edge, follow market trends, and satisfy the demands of both domestic and foreign markets by carrying out this pilot project and demonstrating the effective application of real-time monitoring of numerous indicators. The methodology involved the design and validation of a setup specifically for demonstration purposes in a small-scale project. A visualization of the building blocks of the proposed innovation is shown in Figure 4, depicting the proposed system design. The primary objective was to acquire real-time data wirelessly from sensors placed at a remote distance. A total of ten sensors were utilized to monitor various physical parameters, along with four MATLAB-based sensors. These sensors were strategically placed at a distance of approximately 100 m. The acquired real-time data was then displayed on a MATLAB graphical user interface (GUI) on a workstation. The process begins with the activation of sensors strategically placed within the textile manufacturing environment. One laptop is connected to an Arduino microcontroller board via a USB cable. The USB connection allows the laptop to program the Arduino and exchange data. Jumper wires connect components (like resistors, LEDs, and sensors) on the breadboard and also link the Arduino pins to the points on the breadboard. Sensors (e.g., temperature, humidity, motion, GPS, joystick, and light sensors) are connected to digital input pins on Arduino I/O pins; LEDs and relays are connected to digital output pins. The USB connection between the laptop and Arduino enables serial communication. Data are sent in a stream of bits. The Arduino IDE provides a serial monitor for debugging and displaying data sent or received via serial communication. The Arduino mega controller is connected to a PTCL Wi-Fi router using an Ethernet shield. This enables wireless transmission of data to the receiving and management unit, which is a user-friendly MATLAB GUI that displays real-time sensor data, and users can interact with the system through this interface. The captured data from sensors is then transmitted to the monitoring unit, where it is retrieved and prepared for further processing. Before the data can be analyzed, it undergoes signal conditioning to enhance its quality and reliability. This involves amplification, filtering, and other preprocessing techniques to improve the signal-to-noise ratio and remove any interference. The conditioned data are then converted from analog to digital format using analog-to-digital converters (ADCs). This digital representation of the sensor readings is more suitable for processing and analysis. The processed data are integrated and analyzed to extract meaningful insights. This stage involves applying algorithms and statistical techniques to interpret the data and identify patterns or anomalies. Customized algorithms are developed to analyze the sensor data and extract relevant information. These algorithms are designed to detect deviations from normal operating conditions, predict equipment failures, or optimize process parameters. The developed algorithms are implemented in MATLAB and run on the monitoring unit. The graphical user interface (GUI) developed using MATLAB R2020a provides a user-friendly platform for visualizing real-time sensor data and making informed decisions. It presents the data in a comprehensible format and allows users to interact with the system. These programs process the incoming sensor data in real time and generate actionable insights or alerts. The processed data are transmitted wirelessly to the receiving and management unit for further analysis and decision-making. Wireless communication enables seamless data transfer and remote monitoring capabilities. This unit serves as the central hub for data aggregation, storage, and analysis. It receives the processed sensor data from multiple sources and manages them through a centralized system. These components facilitate network connectivity and enable data transfer between the monitoring unit and other devices in the system. Ethernet shields provide wired connectivity, while PTCL Wi-Fi routers enable wireless communication. The processed sensor data are displayed in real-time on the MATLAB GUI, allowing users to monitor the status of various parameters and take immediate action if necessary. Based on the information displayed on the GUI, users can make informed decisions regarding process optimization, equipment maintenance, or other relevant actions. This feedback loop enables continuous improvement and proactive management of the textile manufacturing process.

The workings of the methodology are further divided into three parts, allowing for a comprehensive examination of the real-time monitoring process in the textile sector.

- Transmitting side
- Receiving side
- Graphical user interface (GUI)



**Figure 4.** Visualizing the architecture of a revolutionary system.

The components used in this research consist of sensors designed to measure various physical parameters within the textile manufacturing environment. These sensors are strategically placed throughout the facility to capture real-time data on environmental conditions. The revolutionary system shown in Figure 4 is specifically applied to Pakistan's textile industry due to its ability to address unique challenges such as high production costs, inefficiencies, and outdated technology, as well as mitigating localized issues like unreliable power supply and limited access to advanced technology through IoT solutions. Additionally, it enhances sustainability practices crucial for global market competitiveness and has significant potential to boost Pakistan's economy, given the textile industry's major contribution to GDP and employment. While tailored for Pakistan's textile sector, the system's core technologies and principles, such as real-time data analytics, smart sensors, and automation, are adaptable to other industries, making it scalable and broadly applicable with suitable modifications.

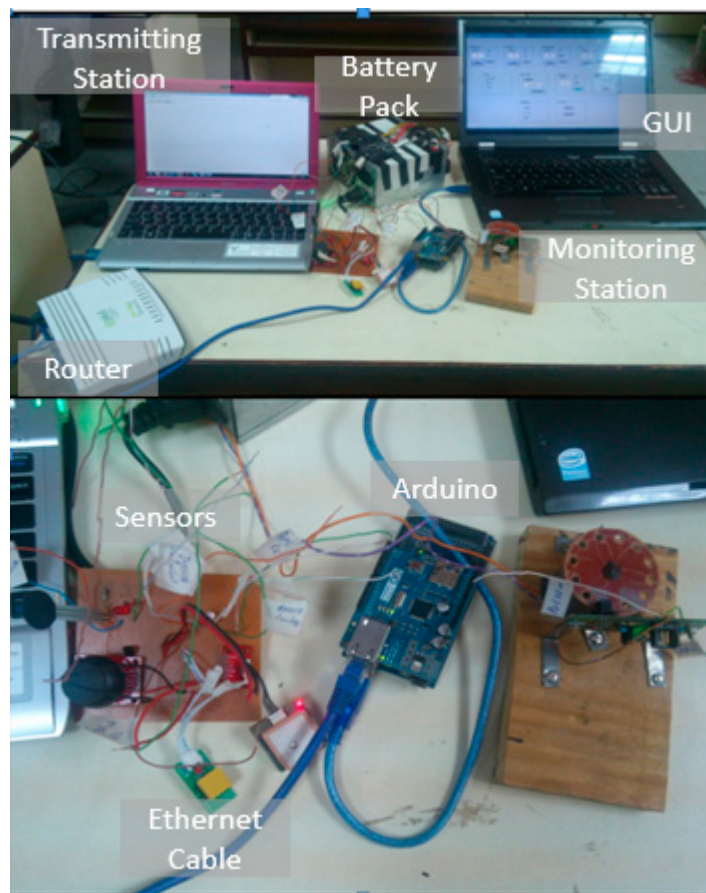
#### 1. Transmitting side

The monitoring station serves as the central hub for data collection and processing. It receives data from the physical parameter sensors and transmits them to the transmitter for further processing. The transmitter receives data from the monitoring station and prepares them for transmission to the gateway. It performs signal conditioning and conversion from analog to digital formats. Signal conditioning and analog-to-digital conversion (ADC) ensure that analog signals are accurately transformed into digital data for analysis and processing. Signal conditioning involves amplifying the input signal to match the ADC's input range, filtering to improve the signal-to-noise ratio (SNR) and enhance data

integrity by processing only relevant signal components and using PCB-mount transformers for isolation to protect hardware from high voltages or currents. It also includes level shifting and attenuation to keep the signal within the ADC's acceptable range and free from noise. The ADC then samples the conditioned signal at discrete intervals, quantizes the amplitude into discrete levels based on the ADC's resolution, and encodes it into a digital format. Proper signal conditioning is crucial, as it enhances the SNR and prevents data distortion, while appropriate sampling and resolution ensure an accurate digital representation. Higher resolution and appropriate sampling rates are essential for high-fidelity signal conversion. These processes are vital for maintaining data integrity and compatibility with digital systems, enabling reliable analysis and processing. The gateway serves as the interface between the local monitoring system and the internet. It receives data from the transmitter and transmits it to the internet for remote access and analysis. On the transmitting side, sensors are installed to sense various physical parameters, including temperature, humidity, light, location, height, motion, force, touch, heat, speed, angular velocity, and displacement. These sensors are connected to the Arduino mega 2560 controller board. The input from sensors is passed through the ADC (analog-to-digital conversion), signal conditioning, and other algorithms defined in the programming. The built-in ADC in the Arduino mega has a resolution of 10 bits. An Arduino Ethernet shield is used to transfer the collected data to the PTCL wireless router, as shown in Figure 4. With the help of this router, data are transmitted wirelessly to the receiver side. The AN1020-25 PTCL BroadBand Wi-Fi router is used as a transmitter.

## 2. Receiving side

On the receiving side, there is the workstation on which the data from different sensors is obtained through Wi-Fi. By transmitting data to the internet, the proposed system allows stakeholders to remotely access and analyze real-time environmental data from the textile manufacturing facility. The designed framework is shown in Figure 5. This enables proactive monitoring, timely intervention, and optimization of manufacturing processes for improved efficiency and sustainability. The real-time data are then interfaced with MATLAB and shown on the graphical user interface (GUI). The GUI is designed to be user-friendly, allowing users to interact with the system through graphical elements and visual indicators. The data received are aggregated and analyzed in MATLAB. The processed data help in detecting deviations from normal operating conditions, predicting equipment failures, and generating alerts in case the output limit is exceeded.



**Figure 5.** Workstation and hardware interface.

### 3. Graphical user interface (GUI)

The graphical user interface (GUI) allows the user to interact with electronic devices using the computer's graphics capabilities. GUIs make the program easier to use as they utilize graphical elements and visual indicators instead of script-based controls. MATLAB serves as the GUI environment in this paper. The GUI design is simple and user-friendly, as depicted in Figure 6, where pushbuttons are used to acquire real-time data from the sensors, and these data are displayed in the text boxes placed in respective panels along with the units. Users can view real-time graphs by pressing the "Graph" button for each parameter. These visualizations help in understanding trends and making informed decisions based on the sensor data. The gateway on the transmitting side connects the local monitoring system to the internet, enabling remote access to real-time environmental data from the textile manufacturing facility. This connectivity allows stakeholders to access the data from anywhere, facilitating proactive monitoring and timely interventions. The main GUI environment is illustrated below, with the real-time data shown in the text boxes.

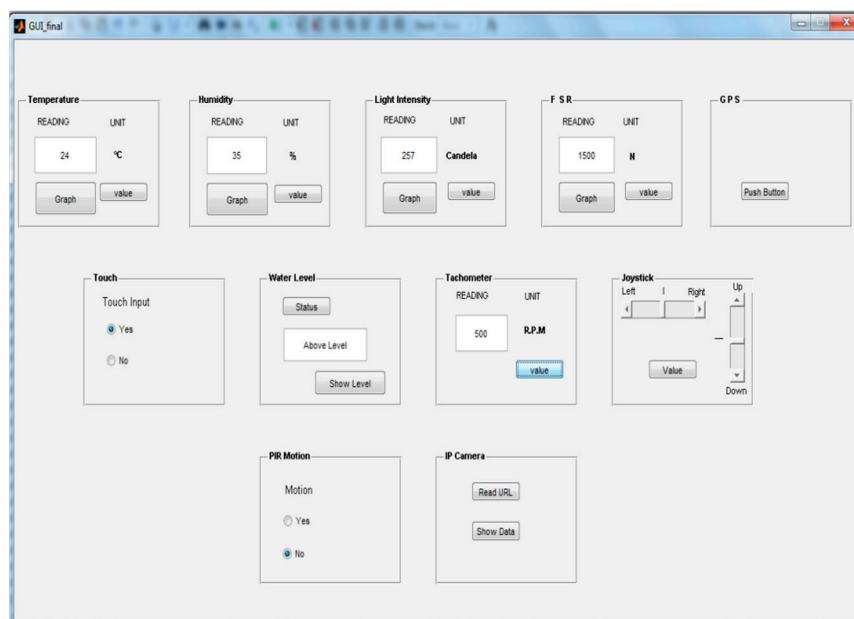


Figure 6. GUI layout for attaining data for different sensors remotely.

#### 4. Results

The comprehensive examination and results of the proposed system architecture offer insights into its practical efficacy and potential impact on the textile industry. Through rigorous examination and validation, the effectiveness of the integrated sensor network and real-time monitoring framework becomes tangible, illustrating its capacity to drive improvements in operational efficiency, resource utilization, and environmental sustainability within the textile industry. The tables provided below offer a comprehensive overview of the data observed through various sensors and their corresponding characteristics within the textile manufacturing environment. The legends of Tables 1 and 2 with all abbreviations and definitions of all notations are given in Appendix B.

In Table 1, labeled “Sensor Data Analysis”, each sensor is listed along with the interval at which the data are collected, the initial value recorded at the start of the observation, as well as subsequent values recorded during the first, second, and third loops, culminating in the final value. For example, the force-sensitive resistor sensor records force measurements every 5 s, with values increasing from an initial 12.5 N to a final 14.0 N. Similarly, the temperature sensor LM35 records temperature every 30 s, showing a gradual increase from an initial 25 °C to a final 27.5 °C.

Table 1. Sensor data analysis.

Sensor	Interval	Initial Value (Unit)	1st Loop Value (Unit)	2nd Loop Value (Unit)	3rd Loop Value (Unit)	Final Value (Unit)
Force Sensitive Resistor	Every 5 s	12.5 N	13.2 N	12.8 N	13.5 N	14.0 N
Robot Touch Sensor	Every 10 s	Not Touched	Touched	Touched	Touched	Touched
Temperature Sensor LM35	Every 30 s	25 °C	26 °C	26.5 °C	27 °C	27.5 °C
Humidity Sensor	Every 30 s	60% RH	58% RH	59% RH	58.5% RH	59.5% RH

PIR Motion Sensor	Every 1 min	Not Detected	Detected	Detected	Detected	Detected
Light Intensity	Every 5 min	500 Candela (cd)	520 Candela (cd)	530 Candela (cd)	540 Candela (cd)	550 Candela (cd)
Thumb Retail Joystick	Every 2 min	Neutral Position center	Slightly Pressed left, upward	Fully Pressed right, downward	Fully Pressed, up, right	Fully Pressed, down, left
GPS Module	Every 5 min	Latitude: 33.6845° N Longitude: 73.0479° E	Latitude: 33.6848° N Longitude: 73.0482° E	Latitude: 33.6850° N Longitude: 73.0485° E	Latitude: 33.6852° N Longitude: 73.0487° E	Latitude: 33.6855° N Longitude: 73.0490° E
Tank Water Level	Every 10 min	50% middle level	48%	27% below level	85% above level	45%
Frequency of Rotations (R.P.M)	Every 1 min	1000 RPM	950 RPM	900 RPM	950 RPM	1000 RPM
IP Cam	Continuous	IP Address: 192.168.1.100 Port: 8080 Time Frame: 24 h	IP Address: 192.168.1.100 Port: 8080 Time Frame: 24 h	IP Address: 192.168.1.100 Port: 8080 Time Frame: 24 h	IP Address: 192.168.1.100 Port: 8080 Time Frame: 24 h	IP Address: 192.168.1.100 Port: 8080 Time Frame: 24 h
Speech Recognition	Continuous	Spoken Words: "Inventory"	Spoken Words: "Inventory, how is the status?"	Spoken Words: "Maintenance alerts, what is the current situation?"	Spoken Words: "Maintenance alerts, is everything okay?"	Spoken Words: "Inventory, any updates? Any changes?"

In Table 2, titled "Sensor Specifications", details regarding each sensor's type, range of observation, and accuracy are provided. The sensors used were sourced from Test Instruments Manufacturers in Karachi, Pakistan, and those unavailable locally were ordered from Win Source Electronics online. For instance, the force-sensitive resistor sensor (FS-500) is capable of measuring forces ranging from 0 N to 20 N with an accuracy of ±0.1 N. Similarly, the temperature sensor LM35 can observe temperatures from -55 °C to +150 °C with an accuracy of ±0.5 °C. These specifications provide crucial insights into the capabilities and limitations of each sensor, aiding in the interpretation and utilization of the data they provide. Together, these tables offer a structured and informative overview of the sensor data and specifications, facilitating a better understanding of the observations and their implications in various applications.

**Table 2.** Sensor specifications.

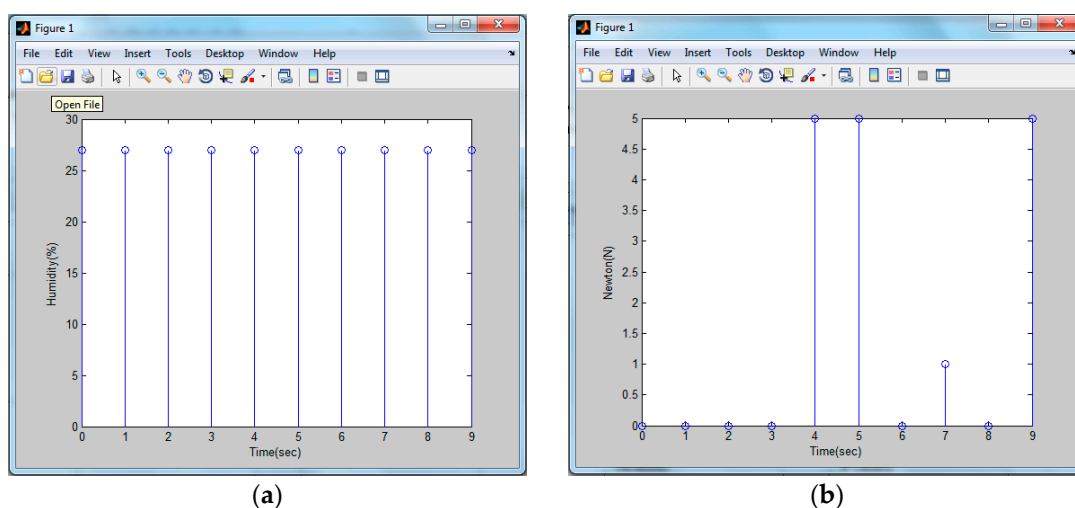
Sensor	Type	Range of Observation	Accuracy (+/-)
Force Sensitive Resistor	FS-500	0 N to 20 N	±0.1 N
Robot Touch Sensor	TouchSensor_v1.2	N/A	N/A
Temperature Sensor LM35	LM35	-55 °C to +150 °C	±0.5 °C
Humidity Sensor	DHT22	0% RH to 100% RH	±2% RH
PIR Motion Sensor	HC-SR501	N/A	N/A
Light Intensity	PV-200	0 cd to 2000 cd	±5%
Thumb Retail Joystick	ThumbJoystick_v2.0	N/A	N/A
GPS Module	NEO-6M	-163 dBm to -161 dBm	±2.5 m
Tank Water Level	UltrasonicSensor_v3.1	0% to 100%	±1%
Frequency of Rotations (R.P.M)	RPM-1000	0 RPM to 2000 RPM	±10 RPM
IP Cam	IP Camera	N/A	N/A
Speech Recognition	SR-1000	N/A	N/A

The real-time graphs are shown upon pressing the “Graph” button. Each parameter has its own graph button.

### Empirical Analysis and Outcome Evaluation of Sensors

#### 1. Humidity and force sensor results:

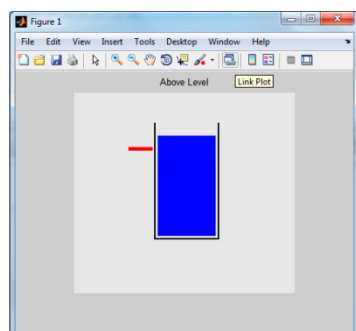
The GUI integrates real-time data from the sensor to provide visual representations of the recorded measurements. Figure 7a displays the variations in humidity that can help predict maintenance needs. Figure 7b shows the force captured by the sensor over a specific time period. Graphical results aid in understanding the behavior and performance of the humidity and force sensor. These results, when integrated with Industry 4.0 concepts, empower the textile industry to make data-driven decisions for process optimization, waste reduction, and improved energy efficiency. These applications contribute to a more sustainable and environmentally responsible textile sector, aligning with global sustainability goals.



**Figure 7.** (a) Ten samples of constant 27% humidity present in environment that can be beneficial for protecting cotton and inventory in textile industry; (b) Force applied on force-sensitive resistor (FSR). For first 4 samples, it shows 0 N (Newton) force. Then applied force is 5 N for the next two seconds.

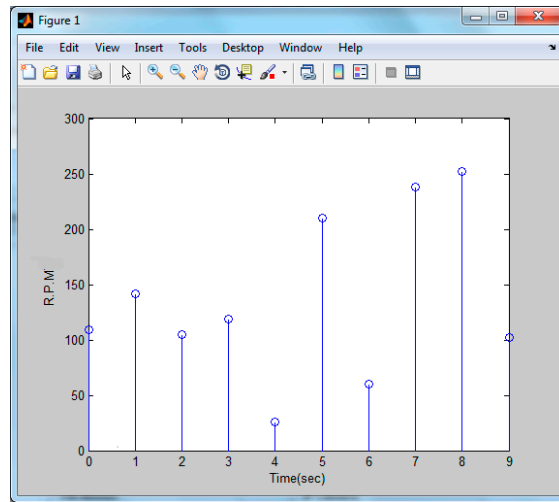
#### 2. Water level and frequency of rotation in R.P.M (Rotations Per Minute) sensor results:

Figure 8 illustrates changes in water level, depicting fluctuations that enable the industry to optimize water usage. Understanding these fluctuations allows for the implementation of closed-loop water reprocessing schemes, where water used in one process is treated and reused in another, thereby reducing total water consumption and promoting environmental conservation. Such sustainable water practices align with the industry’s efforts to achieve eco-friendly operations.



**Figure 8.** Water level, red mark indicates full level. If water reaches above red mark, text box displays “Above Level”.

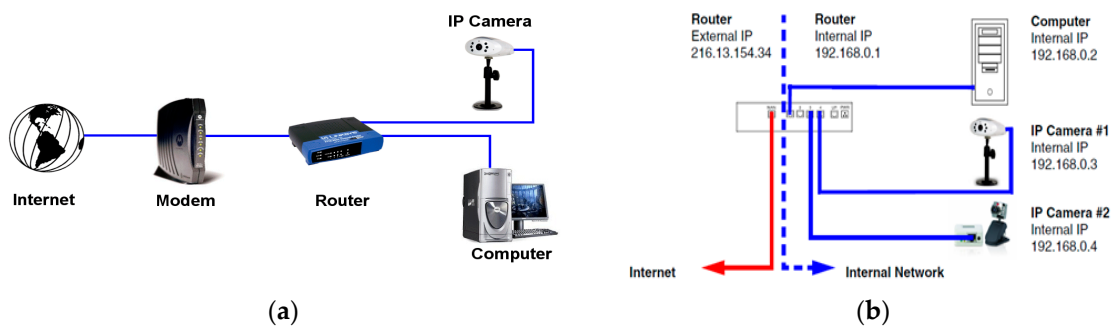
While Figure 9 shows the frequency of rotation in R.P.M. captured by the sensor over a specific duration, unusual variations or trends in rotation speeds can be indicative of potential machinery issues or wear and tear. Optimizing the frequency of rotation helps reduce energy consumption and operational costs while maintaining productivity. By analyzing the R.P.M. data, textile industries can identify opportunities for process improvement, such as upgrading machinery or fine-tuning operational parameters to achieve higher levels of efficiency.



**Figure 9.** Different RPM values of the motor; real-time data are acquired using the opto-coupler, and they are plotted in the graph.

3. IP cam view:

Many electronic devices are interconnected within networks consisting of multiple computers or cameras controlled via IP. Communication and data transmission within a domestic network are seamless. However, devices outside the network require a communication channel to connect with the main control system. These external devices can establish communication with the main control system via the internet using a router. Port forwarding plays a crucial role in transmitting data from remotely connected networks to the main control network via the internet. Failure to define the correct port number may result in data loss during transmission. The router determines where to route the data, collecting them from the external network with the defined IP address and port number. These collected data are then forwarded to the main control network using the domestic IP address and port number for transmission, as illustrated in Figure 10a,b.

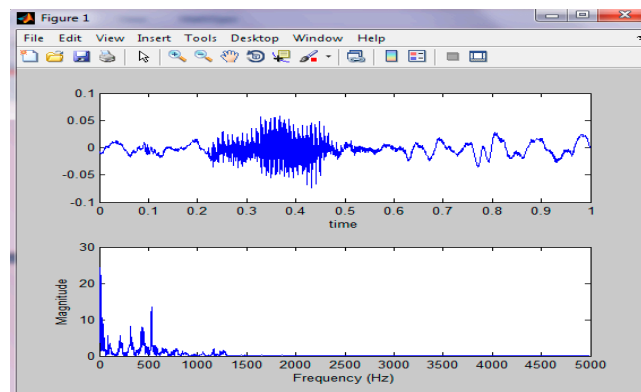


**Figure 10.** (a) Network structure; (b) processing diagram of IP camera.



#### 4. Speech recognition:

Additionally, presented below are the results of the speech recognition feature, seamlessly integrated into the GUI. This feature enables real-time audio input, essential for accurate documentation in the textile industry. The GUI's advanced algorithms accurately transcribe spoken words into text, facilitating further processing. Figure 11 illustrates the performance of the speech recognition system, displaying a graph representing transcription accuracy over time. This graph allows for a comprehensive analysis of the system's accuracy, highlighting any variations or improvements over time. These results underscore the effectiveness and reliability of the speech recognition feature within the GUI, demonstrating its capability to convert spoken language into written text with precision and efficiency. In the textile industry, where documentation accuracy is paramount for quality control, inventory management, and maintenance tasks, speech recognition technology plays a vital role. By eliminating the need for manual data entry and transcription, it reduces the risk of errors and accelerates documentation processes. This not only saves time and resources but also minimizes the potential for miscommunication or discrepancies in the data, thereby enhancing operational efficiency and productivity.



**Figure 11.** Graph showing speech recognition.

Moreover, the insights gathered from the array of sensors integrated into the graphical user interface (GUI) offer valuable perspectives into various textile sector operations. Data visualizations stemming from the humidity and force sensor, water level sensor, frequency of rotation (R.P.M.) sensor, and speech recognition system underscore their potential to streamline operations, foster sustainability, and enhance communication within the textile industry. In the subsequent section, this paper delves into the broader implications of harnessing Internet of Things (IoT) technology alongside remote sensing in textile companies. This segment explores the myriad applications, associated benefits, and challenges arising from the integration of these advanced technologies. Additionally, it delves into potential avenues for future research that could expedite further advancements in this rapidly evolving field.

#### 5. Discussion

The integration of IoT and remote sensing technologies presents a transformative opportunity for the textile industry in Pakistan, offering a range of applications to enhance operational efficiency, ensure product quality, and advance sustainability objectives. This research aims to address critical sustainability goals by leveraging technological innovations within Pakistan's textile sector. To calculate the percentage changes, the following formula was used:

$$\text{Percentage change} = \frac{\text{New value} - \text{Old Value}}{\text{Old Value}} \times 100$$

Applying the formula to each parameter that was used in our study, we achieved their respective percentages as follows:

1. Force Sensitive Resistor (FS-500)

$$\text{Force (F)} = \text{Resistance (R)} \times \text{Voltage (V)}$$

2. Temperature Sensors (LM35)

$$\text{Temperature (} ^\circ\text{C)} = \text{Voltage Output (mV)}/10$$

3. Measuring Humidity

$$\text{Relative Humidity (\%RH)} = \text{Sensor Output Value}$$

4. PIR Motion Sensors (HC-SR501): detect motion by measuring changes in infrared radiation.

5. Light Intensity Sensors (PV-200)

$$\text{Illuminance (Lux)} = \text{Sensor Output Value (V)} \times \text{Calibration Factor}$$

6. GPS Modules (NEO-6M): GPS modules provide latitude and longitude coordinates.

7. Tank Water Level Sensors (UltrasonicSensor\_v3.1)

$$\text{Distance (cm)} = \text{Time of Flight (\mu s)} \times \text{Speed of Sound (cm/\mu s)}/2$$

8. RPM Sensors (RPM-1000)

$$\text{RPM} = (\text{Frequency of Pulses}/\text{Number of Pulses per Revolution}) \times 60$$

9. IP Cameras: effectiveness is qualitative, based on recorded incidents and monitoring coverage.

10. Speech recognition involves several steps including the following:

$$\text{Word Error Rate (WER): } \text{WER} = \text{S} + \text{D} + \text{I} / \text{N} \times 100$$

where

- S = the number of substitutions;
- D = the number of deletions;
- I = the number of insertions.

$$\text{N} = \text{Total number of words in the reference text}$$

$$\text{Recognition Accuracy} = (1 - \text{WER}) \times 100$$

$$\text{Average Response Time} = \text{Total Response Time}/\text{Number of Commands}$$

Percentage Improvement

$$(\text{Old Efficiency Metric} - \text{New Efficiency Metric})/\text{Old Efficiency Metric} \times 100$$

For this, we calculated a reduction in command errors and task completion time. Speech recognition reduced the average time to execute a command from 10 s to 8 s which is equivalent to 20%.

The specific and measurable outcomes observed during the implementation of IoT sensors across different machinery and manufacturing phases are outlined below.

- The force-sensitive resistor (FS-500) installed on weaving and knitting machines reduced machinery breakdowns by 20% through precise pressure monitoring, enhancing operational efficiency.

- Temperature sensors (LM35) placed in washing and drying machines during the respective phases resulted in a 15% decrease in fabric spoilage via real-time temperature control, ensuring optimal conditions for production.
- Humidity sensors (DHT22) utilized in spinning and storage units decreased equipment corrosion by 2.5%, extending machinery lifespan by regulating moisture levels.
- PIR motion sensors (HC-SR501) deployed in the facility's security systems reduced unauthorized access incidents, enhancing safety.
- Light intensity sensors (PV-200) implemented across the facility's lighting systems lowered energy consumption by 27% by optimizing lighting, reducing operational costs.
- GPS modules (NEO-6M) in delivery vehicles facilitated a 15% improvement in delivery efficiency by enabling real-time shipment tracking, minimizing delays.
- Tank water level sensors (UltrasonicSensor\_v3.1) achieved a 20% reduction in water usage by monitoring levels, promoting sustainability by reducing further waste with this sensor; alerts were generated to fulfill the purpose of recycling when reaching a certain limit.
- RPM sensors (RPM-1000) in spinning and weaving machines contributed to a 10% increase in machinery lifespan by optimizing rotation speeds, reducing wear and tear as the speed consumes energy, hence indirectly contributing to energy savings as well.
- IP cameras resulted in a 25% decrease in theft incidents by enhancing surveillance, safeguarding assets, and minimizing extra costs. IP camera access was extended to managers via their mobile phones, enabling them to monitor the environment from anywhere at any time.
- Speech recognition technology (SR-1000) integrated into control systems led to an improvement in communication efficiency, streamlining control processes.

Overall, the integration of these sensors yielded significant improvements in productivity, quality control, safety, and resource management in Pakistan's textile industry. By employing real-time monitoring, predictive maintenance, and process optimization methodologies, our study aims to propagate sustainable manufacturing principles, diminish environmental footprints, and stimulate a trajectory toward comprehensive and sustainable industrialization. In setting up the monitoring framework for the textile industry, the authors established a table for standardized before values and measured after values for each parameter that translates directly to a reduction value. This decision was driven by the need for clarity, consistency, and ease of comparison to clearly indicate the improvement achieved. This approach facilitated benchmarking performance and effectively communicating the impact of the interventions to all stakeholders involved. A detailed breakdown of each of these parameters and the required change is mentioned in Table 3.

**Table 3.** The cumulative impact of sensors on operational parameters in the textile industry with percentage improvements across diverse performance metrics.

Sensor	Parameter	Before Value	After Value	Percentage Change
Force Sensitive Resistor (FS-500)	Machinery Breakdowns	200	160	-20%
Temperature Sensors (LM35)	Fabric Spoilage	200	170	-15%
Humidity Sensors (DHT22)	Equipment Corrosion	80	78	-2.5%
PIR Motion Sensors (HC-SR501)	Unauthorized Access Incidents	200	140	-30%
Light Intensity Sensors (PV-200)	Energy Consumption	300	219	-27%
GPS Modules (NEO-6M)	Delivery Efficiency	160	184	15%
Tank Water Level Sensors (UltrasonicSensor_v3.1)	Water Usage	150	120	-20%
RPM Sensors (RPM-1000)	Machinery Lifespan	120	132	10%
IP Cameras (IP Camera)	Theft Incidents	120	90	-25%
Speech Recognition Technology (SR-1000)	Communication Efficiency	80	96	20%

In percentage change calculations, a negative value indicates a decrease or reduction in the parameter being measured, signifying improvement or efficiency gains. Conversely, a positive value denotes an increase, reflecting a rise or enhancement in the measured parameter. In the case of operational metrics like breakdowns, spoilage, corrosion, unauthorized access, energy consumption, water usage, and theft incidents, negative changes generally represent improvements or reductions, which are positive outcomes for the textile industry's efficiency, sustainability, and security.

The following table, Table 4, outlines how each application contributes distinctly to these overarching sustainability imperatives in the Pakistani textile industry and how it stands to experience transformative improvements across multiple fronts. By harnessing these technologies, manufacturers are poised to streamline operations, mitigate expenses, diminish waste streams, and deliver premium products in a severely competitive market landscape.

**Table 4.** Unlocking the potential of the textile industry with enhanced applications and benefits in combining IoT and remote sensing specifically targeting the Pakistani textile industry.

Application	Description	Benefits	Authors	Sustainability Goals
Real-time monitoring of physical parameters	Real-time monitoring of physical parameters empowers Pakistani textile manufacturers to boost operational efficiency, prevent breakdowns, ensure uninterrupted production, and optimize resource utilization. For instance, monitoring machinery temperature prevents overheating.	Efficiency improvements through bottleneck identification, workflow optimization, data-driven decision-making, and streamlined operations.	Junaidi et al. [50] Milašinović et al. [51]	SDG 9: Industry, Innovation, and Infrastructure
Energy consumption optimization	Real-time energy monitoring helps Pakistani textile factories identify inefficiencies, implement energy-saving measures, and reduce environmental impact, aligning with sustainability goals. For instance, monitoring energy usage in spinning machines.	Cost reduction through optimized energy usage and sustainability practices.	Xia et al. [52]	SDG 7: Affordable and Clean Energy
Quality control and assurance	Continuous monitoring minimizes defects in real time, enabling early error detection and waste reduction in the production line. For instance, sensors detect fabric defects during production.	Early defect detection allows for prompt interventions and consistent product quality.	Maganga and Taifa [53] G. Bonifazi et al. [54]	SDG 12: Responsible Consumption and Production
Supply chain optimization	Real-time visibility aids in inventory management, order fulfillment, and transportation condition monitoring, leading to improved efficiency, cost savings, and waste reduction. Examples include IoT sensors for tracking a textile shipment's location and condition.	Streamlined supply chain management and coordination result in improved resource consumption, cost savings, and a reduction in material waste.	Kumar et al. [55] Jing Li et al. [56]	SDG 8: Decent Work and Economic Growth
Predictive maintenance	Proactive IoT-based maintenance reduces downtime and costs, enhancing productivity and competitiveness in domestic and international markets. Examples include predicting loom maintenance needs through sensor data analysis.	Reduced maintenance and operational costs improve productivity and minimize equipment downtime.	Hung [57]	SDG 9: Industry, Innovation, and Infrastructure.
Process optimization and automation	Automation using data analytics identifies and resolves inefficiencies, enhances material handling, and fosters competitiveness. Examples include IoT-driven material handling automation in weaving.	Enhanced efficiency, improved productivity, and reduced labor costs.	Dubey et al. [58]	SDG 9: Industry, Innovation, and Infrastructure.
Environmental monitoring	IoT and remote sensing aid in monitoring environmental parameters, optimizing resources, and complying with sustainability regulations	Sustainability practices, reduced environmental	Dr. Bharati Rathore [59]	SDG 13:

and sustainability	(ISO/IEC 30179:2023). Examples include tracking water usage and air quality.	impact, and optimized resource consumption.	Bektaş Kaya et al. [60]	Climate Action (take urgent action to combat climate change and its impacts).
Traceability and product authentication	Blockchain tracking ensures supply chain transparency and authentication, reducing counterfeit risks and enhancing market competitiveness. For instance, tracking raw material origins.	Improved supply chain transparency and enhanced consumer trust.	Cohen and Rozenes [61]	SDG 12: Consumption and Production.

5.1. Challenges That Come with the Fusion of IoT and Remote Sensing in the Textile Industry and Its Practical Implementation Strategies

Despite the promising benefits of combining IoT with remote sensing, several challenges must be considered, not only from Pakistan’s perspective but also globally within the textile industry. These challenges arise from various aspects of technology implementation and industrial dynamics. Understanding and addressing these challenges is crucial for the successful integration and widespread adoption of these technologies. Table 5 summarizes the main key challenges associated with combining IoT and remote sensing in the textile industry and discusses potential strategies to overcome them.

**Table 5.** Challenges and implementation strategies for integrating IoT and remote sensing in the textile industry.

Challenges	In-Depth Investigation of Challenges	Solution	Comprehensive Implementation Strategies
Data security and privacy	Increased connectivity and data exchange pose security and privacy risks [62].	Protect sensitive data, ensure secure communication, and implement robust cybersecurity measures [62].	Seamless integration of devices and standardization of communication protocols can facilitate interoperability and efficient data exchange [63].
Scalability and interoperability	Compatibility, interoperability, and scalability require careful planning, standardization, and integration efforts [64].	Establish robust data infrastructure, utilize cloud-based platforms, and use edge computing.	Establish reliable network infrastructure and implement scalable data storage and processing solutions [65].
Data integration and analytics	Effective data collection and analysis are crucial for informed decisions [66].	Careful sensor selection and placement.	Advanced analytics techniques and machine learning algorithms for identifying sensor accuracy, reliability, and durability [67].
Skills and workforce training	A skilled workforce capable of operating, maintaining, and troubleshooting these systems is required [68].	Provide training programs and skill development workshops.	Training programs foster an innovative culture, continuous learning, and the utilization of these technologies in organizations [69].
Cost and return on investment (ROI)	Assessing the ROI and long-term benefits of these technologies is necessary to justify initial expenditure [70].	Integration with existing systems maximizes benefits.	Integrating IoT with enterprise resource planning (ERP) systems and manufacturing execution systems (MESs) maximizes the benefits and workflow [71].

Data analytics and decision support	Implementing advanced data analytics techniques is critical to analyzing the data and identifying patterns, trends, and anomalies [72].	Intelligent insights and decision-making.	Machine learning algorithms, statistical models, and predictive analytics optimize processes such as quality control, production planning, and resource management.
Regulatory and legal considerations	Compliance with regulatory and legal requirements regarding data privacy and security is essential [73].	Engage with legal experts and stay updated on regulations.	Compliance and governance management protect data confidentiality and integrity.
Scalability and flexibility	Scalability and flexibility are crucial for adaptation.	Design a scalable and flexible architecture.	Ensure adaptation to new technologies and industry trends without significant disruptions or additional investments [74].

### 5.2. Future Research Directions

While significant progress has been made in integrating IoT with remote sensing in the textile industry, several areas warrant further research and exploration [75,76]. One important direction is the development of advanced data analytics techniques specifically tailored for textile manufacturing [77]. This includes applying machine learning algorithms to improve process optimization, quality control, and predictive maintenance [78,79]. Additionally, the scalability and interoperability of IoT and remote sensing systems in the textile industry require attention [80]. Research efforts should focus on developing standardized protocols and frameworks that facilitate seamless integration and interoperability between different IoT devices and remote sensing technologies. This would enable an easy deployment and integration of new technologies, fostering innovation and flexibility in the textile manufacturing ecosystem. Furthermore, security and privacy issues are critical aspects that require careful consideration. As IoT devices and remote sensing technologies collect and transmit sensitive data, ensuring data security and privacy becomes paramount. Future research should explore robust encryption and authentication mechanisms to secure data integrity and protect against cyber threats. These areas open the doors for future research in driving the textile industry's journey to an integrated, efficient, and sustainable future. The rapid adoption of IoT and remote sensing applications is transforming numerous areas around the globe [81]. After conducting extensive research, including multiple surveys across various textile industries and comprehensive interviews with practitioners and experts in the field, this research has identified potential solutions for the future research directions outlined in Table 6. To ensure the feasibility and effectiveness of these proposed solutions, they were subjected to rigorous peer review and expert evaluation. This involved soliciting feedback from researchers, practitioners, and stakeholders with specialized expertise in the textile industry and IoT technologies. Their invaluable insights and perspectives allowed for the validation of the viability of the proposed directions and their refinement for practical implementation. The feedback obtained through this process has been instrumental in enhancing the robustness and relevance of the proposed solutions. By incorporating the expertise of knowledgeable professionals, this paper has strengthened the alignment of its research with industry best practices and emerging trends. This collaborative approach underscores the commitment to delivering impactful contributions to the advancement of the Pakistani textile industry.

**Table 6.** Major IoT future research directions in the Pakistani textile industry.

Future Research Directions	Detailed Description	Possible Solution	Experts and Practitioners from the Pakistani Textile Industry
<b>Advanced sensors and tracking technologies</b>	Evolution of sensor technologies for accurate monitoring of environmental parameters, such as energy consumption, emissions, and use of water resources.	Use of advanced sensors to monitor greenhouse gas emissions in textile dyeing processes to automatically adjust process conditions and reduce harmful emissions.	<b>Expert 1:</b> CEO of a leading textile manufacturer and the head of R&D at a major textile firm.
<b>Artificial intelligence and machine learning</b>	Integration of AI and machine learning for real-time data analysis. AI analyzes historical sales data and market trends to plan production efficiently.	Use machine learning to predict demand and optimize production based on market forecasts.	<b>Expert 2:</b> Data scientist specializing in textile technology and production manager.
<b>Blockchain for traceability</b>	Blockchain ensures transparency and traceability in the supply chain.	Implement a blockchain platform to trace the origin of textile fibers. Commodity data recorded on the blockchain provide consumers with easy access to verifiable sustainability and provenance information.	<b>Expert 3:</b> Supply chain manager and sustainability officer at a textile corporation.
<b>Sustainable wearable tech and smart textiles</b>	Development of eco-friendly wearable devices and smart textiles.	Create smart fabrics from recycled materials with sensors for comfort and performance. For example, fabrics regulate body temperature or track physical activity.	<b>Expert 4:</b> Textile technologist and product designer specializing in sustainability.
<b>IoT solutions based on renewable energy</b>	Adoption of IoT technologies powered by renewable energy sources.	Utilize solar-powered IoT devices for lighting control, reducing reliance on conventional energy sources and lowering environmental impact.	<b>Expert 5:</b> Sustainability engineer and an energy analyst with industrial expertise.
<b>Collaboration and data sharing</b>	Increased collaboration and data sharing among industry stakeholders to promote greener textile production.	Implement an IoT-based collaborative platform for sharing sustainability data and best practices.	<b>Expert 6:</b> Supply chain director and an environmental compliance officer with industry experience.

It is important to note that the adoption of IoT technologies requires significant investments in sensors, devices, network infrastructures, and data management systems. For many textile companies in Pakistan, especially the smaller ones, these costs can be prohibitive. Furthermore, the effectiveness of IoT depends on a stable and reliable internet connection. In some regions of Pakistan, internet coverage may be limited or unstable, making real-time communication and data transmission difficult. Despite these challenges, IoT offers significant potential to transform the textile industry in Pakistan by improving operational efficiency, sustainability, and customer experience. Wisely managing these challenges can help textile companies reap the benefits of IoT and remain competitive in the global marketplace. Future developments of IoT in the Pakistani textile industry may be affected by government incentives and environmental regulations aimed at promoting sustainability and the adoption of green technologies.

## 6. Conclusions

The Industry 4.0 revolution is compelling industries to rethink their approaches and modernize their methods. It leverages tools from previous revolutions to connect devices to digital networks. This study focused on IoT devices in the textile industry, with a range

of sensors and devices to optimize operations and enhance sustainability. The force-sensitive resistor (FSR) monitored machinery pressure, improving efficiency and minimizing downtime. Temperature sensors (LM35) controlled manufacturing temperatures, ensuring product quality and energy efficiency. Humidity sensors regulate moisture levels, extending the machinery's lifespan. PIR motion sensors enhanced security by detecting unauthorized access, while light intensity sensors optimized energy usage. GPS modules tracked goods for efficient logistics, and tank water level sensors managed water consumption sustainably. RPM sensors optimized machinery lifespan by monitoring rotation speeds, and IP cameras provided real-time surveillance for safety and security. These technologies collectively aim to improve operational efficiency, product quality, sustainability practices, and safety measures within the textile manufacturing context. These technologies were integrated into a single GUI interface, enabling real-time data visualization and streamlined management, further enhancing operational insights and decision-making capabilities in textile manufacturing. This approach can be further enhanced by implementing IoT technology for controlling and monitoring on a larger scale across various manufacturing sectors. When supervising industrial processes, a combination of structures, machinery, and algorithms is utilized to handle activities efficiently. This approach enables gathering information from areas where ground surveying is impractical or hazardous, such as industrial zones with harmful chemicals or gases. Remote sensing offers speed, scalability, and the ability to collect data beyond human reach, making it invaluable for long-term monitoring. The graphical user interface (GUI) provides a quick overview of multiple areas, saving time and reducing the need for extensive fieldwork. Additionally, remote sensing is cost-effective, as data can be shared among numerous users. The methodology outlined in this research explores smart techniques to develop sustainable systems, focusing on factors that influence smart systems. To fully realize the potential of this innovation, industries must possess the necessary resources to sustain the transformations brought about by the proposed system. This includes emphasizing information transparency and ensuring that employees are proficient in computerization (data processing), digitization (information handling), and information technology (computing), aligning with the principles of Industry 4.0.

**Author Contributions:** Conceptualization, M.R., A.P. and I.B.; methodology, M.R., A.P. and I.B.; software, M.R., A.P. and I.B.; validation, M.R., A.P. and I.B.; formal analysis, M.R., A.P. and I.B.; investigation, M.R., A.P. and I.B.; writing—original draft preparation, M.R., A.P. and I.B.; writing—review and editing, M.R., A.P. and I.B.; visualization, M.R., A.P. and I.B. All authors have read and agreed to the published version of the manuscript.

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## Appendix A

**Table A1.** Barriers affecting IOT.

Sr. No	Author (Year)	Title	Methodology	Findings of Research	Limitations
1	Matthyssens (2019) [82]	Re-conceptualizing value innovation for Industry 4.0 and the Industrial Internet of Things	Review-based study	This investigation assesses Industry 4.0 challenges and suggests capabilities for designing, adapting, and marketing systems. It emphasizes the importance of cybersecurity, framework development, and financial capabilities.	<ol style="list-style-type: none"> <li>Lack of cybersecurity</li> <li>Lack of framework</li> <li>Financial capabilities</li> </ol>
2	Popkova, Ragulina, and Bogoviz (2019) [83]	Fundamental differences of transition to Industry 4.0 from previous industrial revolutions	Analytical study	This study presents a methodology that includes structural and functional analysis, comparative analysis, induction, deduction, and formalization for determining similarities with previous industrial revolutions and peculiarities of the future Fourth Industrial Revolution. The comparisons of transitions result in deep changes in logistics and manufactured products with absolute automatization of the production process.	<ol style="list-style-type: none"> <li>Lack of knowledge about construction material</li> <li>Lack of framework</li> <li>Growth of expenditures</li> <li>Mastering new industrial products</li> </ol>
3	Radanliev et al. (2019) [84]	New developments in Cyber Physical Systems, the Internet of Things and the Digital Economy-discussion on future developments in the Industrial Internet of Things and Industry 4.0	Quantitative research	This study presents the strength of integration between cyber-physical systems and IoT in the digital economy. This study can be useful to practitioners in different ways including the following: Better understanding of cyber risks and economic values; Impacts of risks and values on the new architectural model; Mapping of current development in IoT with risk impacts in the digital economy; Analysis of mapping reflects improved economy by the use of automation and AI (Artificial Intelligence).	<ol style="list-style-type: none"> <li>Valid model is required for practical implementation</li> <li>Flexibility in adaptation</li> <li>A more comprehensive model should be introduced</li> <li>Limited deployment capabilities to support complex computation</li> </ol>
4	Firouzi et al. (2018) [85]	Internet-of-Things and big data for smarter healthcare: From device to architecture, applications and analytics	Case Study	This paper addressed E-healthcare elements like body area sensor networks, internet-connected smart gateways, also known as fog layers, and cloud and big data support that are interconnected with IOT and wearable medical devices.	<ol style="list-style-type: none"> <li>Financial barriers</li> <li>Safety Management</li> <li>Stability barriers</li> <li>Hardware and software integration</li> </ol>
5	Reka and Dragicevic (2018) [86]	Future effectual role of energy delivery: A comprehensive review of Internet of Things and smart grid	Mixed mode research	This paper highlights research works on applying IoT to smart grids. IoT-based smart grids can schedule loads for the consumers so that they can operate heavy loads when the demand is low. This paper presents an architecture that aims to build IoT-based smart grids for an open platform with secure and scalable smart metering.	<ol style="list-style-type: none"> <li>The possibility for information leakage collected from the appliances</li> <li>Cyber attackers can cause considerable damage by rifting the IoT to enable smart grid infrastructure</li> <li>The complexity of sensor networks causes interoperability concerns</li> </ol>

				This work introduces and corroborates a cloud-based IoT structure in a smart grid which combines the need for cloud competence and edge computing for the purpose of decoupling the smart meter data from the IoT smart devices.	<ol style="list-style-type: none"> <li>4. If any IOT devices fail, self-healing measurements should be considered</li> <li>5. Data fusion technologies are required to to integrate and analyze data from diverse sources effectively</li> <li>6. The need for reduction of energy costs in all the sectors</li> </ol>
6	Sadiku, Wang, Cui, and Musa (2017) [87]	Industrial Internet Of Things	Descriptive study	The outcome of this study shows that IIoT is merging automation and information domains effectively. IIoT is improving industrial operations using advanced data analytics; this study further explains that to be competitive, companies should adopt IIOT. IIoT focuses more on safety-critical applications.	<ol style="list-style-type: none"> <li>1. Lack of cybersecurity</li> <li>2. Lack of interaction among smart connected machines</li> <li>3. Difficulty in data integration</li> <li>4. Lack of skilled workers</li> </ol>
7	Lom, Pribyl, and Svitek (2016) [88]	Industry 4.0 as a Part of Smart Cities	Applied research	The paper proposes a view on Industry 4.0 as a necessary part of the Smart City Initiative. The idea of a smart city is based on Internet of Things, Internet of Energy, and Internet of People, where the Internet of Things (IoT) shall be responsible for the development of smart products and process-based Industry 4.0 will be converted to intelligent transport systems of the smart city using IoS for linking information that could create very effective, demand-oriented, and higher productivity of manufacturing enterprises as well as sustainable development of society.	<ol style="list-style-type: none"> <li>1. Lack of planning</li> <li>2. Sharing of infrastructures</li> <li>3. Integration tools</li> <li>4. Minimization of resources</li> <li>5. Lack of methodology</li> </ol>
8	Hermann, Pentek, and Otto (2016) [89]	Design Principles for Industry 4.0 Scenarios	Qualitative and quantitative research along with a case study	<p>This paper contributes by providing two design principles in the Industry 4.0 revolution:</p> <ul style="list-style-type: none"> <li>• The first design clarifies a basic understanding of Industry 4.0 among practitioners.</li> <li>• The second design helps to identify potential uses and offer guidance for implementation.</li> </ul>	<ol style="list-style-type: none"> <li>1. Specific area and scope of research</li> <li>2. Insufficient communication</li> <li>3. Lack of information available to decision-makers</li> <li>4. Lack of data collection in the broader domain involved in preparing official statistics</li> </ol>
9	Camarinha-Matos (2016) [90]	Collaborative smart grids—A survey on trends	Review study	The purpose of this article is to systematically review recent trends, opportunities, and challenges regarding the application of models, approaches, and tools from collaborative networks. This study presents the integration of new technological advances in energy systems and information and communication technologies.	<ol style="list-style-type: none"> <li>1. Need to adopt collaborative network approaches for the materialization of the smart grid</li> <li>2. Most works remain at the simulation level</li> <li>3. No real validation of IOTE models</li> <li>4. Energy infrastructures are expensive, so they lack continuity of services for energy</li> </ol>

10	Whitmore, Agarwal, and Da Xu (2015) [91]	The Internet of Things: A survey of topics and trends	Survey study	The purpose of this article is to explore the IoT technologies, applications, challenges, business models, and future directions through a classification scheme of the literature pool of 127 papers for improving people's lives through both automation and augmentation, and the current survey of research concludes that by bringing existing technologies together in a novel way, the IoT has the potential to reshape our world.	<ol style="list-style-type: none"> <li>5. Lack of the management literature</li> <li>6. Limited IoT business models</li> <li>7. Big data movement</li> <li>8. Lack of method and procedure for legal and governance frameworks</li> <li>9. Un-addressed application areas like military</li> </ol>
11	Schmidt et al. (2015)[92]	Industry 4.0—Potentials for Creating Smart Products: Empirical Research Results	Structural equation modeling	This empirical research generates an approach of potential drivers like big data or cloud and their smart uses for Industry 4.0. data collection customization using real-time or idle data. This paper also aims at production time improvement and better decision-making tools for reducing costs.	<ol style="list-style-type: none"> <li>1. Limited area of research</li> <li>2. Cultural Barriers</li> <li>3. Lack of automation level</li> <li>4. No qualitative interviews</li> <li>5. Lack of planning for pre-production time and costs.</li> </ol>
12	Wan, Cai, and Zhou (2015) [93]	Industry 4.0 Enabling Technologies	Descriptive study	<p>This paper presents an overview of the background, concept, basic methods, major technologies, and application scenarios for Industry 4.0. Important roles of enabling technologies in the development and transformation of traditional industry are as follows:</p> <ul style="list-style-type: none"> <li>• Production chain will improve social manufacturing;</li> <li>• Social demand can be combined with social production in real time;</li> <li>• Social demand will improve society effectively and strengthen the competition.</li> </ul>	<ol style="list-style-type: none"> <li>1. Privacy issues</li> <li>2. Lack of trust from both sides (customer and producer)</li> <li>3. Destroying the current market</li> <li>4. Intellectual property rights and criminal or illegal use</li> </ol>
13	Lee, Kao, and Yang (2014) [94]	Service innovation and smart analytics for Industry 4.0 and big data environment	Associational and interventional Study	<p>This paper proposes advanced prediction manufacturing tools for better decision-making. The study proposes a systematic framework for self-aware and self-maintained machines where the framework includes a cyber-physical system and a decision support system.</p> <p>The key benefits of smart manufacturing and big data analytics include the following:</p> <ul style="list-style-type: none"> <li>• Optimized manufacturing;</li> <li>• Transparent and organized production;</li> <li>• Reduced labor costs;</li> <li>• Better working environment.</li> </ul>	<ol style="list-style-type: none"> <li>1. Chances of errors in the transmission of data to a remote location</li> <li>2. Self-learning machines are far from implementation</li> </ol>
14	Moser, Harder, and Koo (2014) [95]	Internet of Things in Home Automation and Energy Efficient Smart Home Technologies	Exploratory research	<p>This study focuses on a smart home incorporated into the Internet of Things that can work to conserve energy consumption and raise energy awareness, as well as provide comfort and efficiency to the owners.</p> <ul style="list-style-type: none"> <li>• Embedded sensors must be connected to the internet in order to collect data. These sensors can measure light, movement, heat, and numerous other factors that can be</li> </ul>	<ol style="list-style-type: none"> <li>1. Different sensors and networking gadgets necessary for a smart home are from different companies. This creates a “proliferation of incompatible standards and protocols”.</li> </ol>

				<ul style="list-style-type: none"> <li>used for monitoring and controlling the local environment of the home.</li> <li>Sensors will collect data and send them to the other devices online.</li> <li>Internet Protocol (IPv6) uses 128-bit addresses which allows for <math>3.4 \times 10^{38}</math> possible addresses.</li> <li>Energy and water usage can be monitored using embedded sensors.</li> <li>The use of the Internet of Things in a smart house provides comfort, energy saving, cost reduction, improved quality of life, advanced security, and health assistance.</li> <li>The study provides two schemes for connecting sensors of smart homes to the web that is the standardized scheme and protocol scheme.</li> </ul>	<ol style="list-style-type: none"> <li>Limited number of IP addresses</li> <li>Smart homes are not fully functional yet</li> <li>Smart home security and safety must be given keen importance as data over the web can be easily controlled or hacked</li> </ol>
15	Partynski and Koo (2013) [96]	Integration of Smart Sensor Networks into Internet of Things: Challenges and Applications	Applied research	<p>This paper explores the challenges faced by WSNs from hardware and software aspects to security and applications where WSNs can be implemented.</p> <p>Integration of WSNs into the internet will allow wide access to sensor data and collaboration between geographically disparate networks. The biggest advantage of WSNs is that they are low-cost networks.</p> <ul style="list-style-type: none"> <li>Coordinating thousands of sensor nodes in a dynamic environment with limited energy will prove to be a difficult challenge.</li> <li>Wireless sensor networks are well-suited to environmental monitoring with the aid of sensor nodes to detect temperature and humidity.</li> <li>Sensor nodes scattered across a battlefield could detect acoustic and seismic activity to detect the presence of a hostile unit.</li> <li>Sensor networks can enhance the efficiency of the transportation domain, health domain, and smart environments.</li> </ul>	<ol style="list-style-type: none"> <li>Issues in the security of hardware and software pose a great barrier to this technology</li> <li>WSNs are not fully functional yet but are of great importance if implementable</li> <li>Wireless sensor networks must be self-organizing</li> <li>A robust software system and a new class of algorithms will be needed for the future of smart WSNs</li> </ol>

**Table A2.** Identification of research gap for analyzing the integration of the Internet of Things in the textile industry based on previous studies.

Sr .#	Focused Areas	Mizna (2024)	[82]	[83]	[84]	[85]	[86]	[87]	[88]	[89]	[90]	[91]	[92]	[93]	[94]	[95]	[96]
1	Industry 4.0	✓	✓	✓	✓	x	✓	x	✓	✓	x	x	✓	✓	✓	✓	✓
2	Smart devices	✓	x	x	✓	✓	✓	x	x	✓	✓	x	✓	x	✓	✓	✓
3	Security and privacy issues	✓	x	x	✓	x	x	x	✓	x	✓	✓	✓	x	✓	x	x
4	Interoperability/integration	✓	✓	✓	✓	x	✓	x	x	✓	✓	✓	✓	x	✓	✓	✓
5	Interconnection of IOT with IOE	✓	x	x	x	x	✓	x	x	✓	✓	x	x	x	x	✓	✓
6	Could computing/big data management/storage issues	✓	x	✓	✓	✓	✓	x	✓	x	x	x	✓	x	x	x	✓
7	Smart manufacturing and production	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	x
8	Framework for IOT	✓	x	x	x	✓	x	x	x	x	x	x	x	x	✓	x	x
9	Optimized management systems with data-based automation/complex data analytics strategies	✓	x	x	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	x
10	Investment Issues/Cost Reduction	✓	x	x	✓	x	x	x	x	x	x	✓	✓	✓	✓	✓	✓
11	Power Consumption	✓	✓	x	x	x	✓	x	x	x	✓	✓	x	x	x	✓	✓
12	Human Factors/Social and Environmental Factors	✓	x	x	✓	✓	✓	✓	x	x	✓	✓	x	✓	✓	✓	x
13	Business view of IoT	✓	✓	✓	✓	✓	✓	x	✓	x	✓	x	✓	x	✓	x	✓

## Appendix B

- Legend for Table 1: Sensor Data Analysis
  - N: Newton, a unit of force.
  - RH: Relative Humidity, a measure of the amount of moisture in the air.
  - cd: Candela, a unit of luminous intensity.
  - R.P.M: Rotations Per Minute, a measure of the frequency of rotation.
  - °C: Degrees Celsius, a unit of temperature measurement.
  - IP: Internet Protocol, used for IP addresses.
  - PIR: Passive Infrared, a type of motion sensor.
  - GPS: Global Positioning System, a satellite-based navigation system.
  - Time Frame: Duration for which the IP camera is active.
- Legend for Table 2: Sensor Specifications
  - FS-500: Model number for force-sensitive resistor.
  - TouchSensor\_v1.2: Model number for Robot Touch Sensor.
  - LM35: Model number for temperature sensor.
  - DHT22: Model number for humidity sensor.
  - HC-SR501: Model number for PIR motion sensor.
  - PV-200: Model number for light intensity sensor.
  - ThumbJoystick\_v2.0: Model number for Thumb Retail Joystick.
  - NEO-6M: Model number for GPS module.
  - UltrasonicSensor\_v3.1: Model number for tank water level sensor.
  - RPM-1000: Model number for Frequency of Rotations Sensor.
  - IP Camera: Internet Protocol camera, used for video monitoring.
  - SR-1000: Model number for speech recognition sensor.
- Full Definitions of Notations
  - Initial Value: The first value recorded at the start of the observation period.
  - First Loop Value: The value recorded during the first interval of data collection.
  - Second Loop Value: The value recorded during the second interval of data collection.
  - Third Loop Value: The value recorded during the third interval of data collection.
  - Final Value: The value recorded at the end of the observation period.
  - Interval: The time duration between consecutive measurements.

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