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Apparel 4.0: A Review of the Apparel Industry's Adoption of Frontier Technologies

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Abstract
The Textile & Apparel (T&A) industry has been recognized for its modest shifts. This review paper, however, has examined the state of the apparel industry's technology adoption, with special reference to 4IR technologies and fast-evolving market preferences in the post-pandemic era. Based on an extensive literature survey, the study concludes that the fourth industrial revolution (4IR) technologies have started gaining ground and disrupting the global apparel value chain. Likewise, Covid-19 too has brought considerable disruptions, driving organizational changes faster than ever. On one hand, Covid-19 has caused a significant adverse impact on the apparel industry, impacting brands, producers, and workers across the world. On the other hand, it has accelerated the adoption of frontier technologies by the industry. The Fourth Industrial Revolution (4IR) is transforming the apparel sector in design, development, production, supply chain, and marketing value segments. Besides process automation, frontier 4IR technologies such as 3D knitting and printing, robotics and intelligent manufacturing, virtual and augmented reality, artificial intelligence, business analytics, IoT, etc., have started shaping the future of the T&A industry. The paper should be of interest to both market actors (e.g., producers and marketers) and market facilitators (e.g., policymakers and academia).
Keywords: Textile & Apparel (T&A) industry, Fourth Industrial Revolution (4IR), COVID-19, frontier technologies, fashion cycle, automation, biotechnology, apparel 4.0
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1. Introduction

The Textile & Apparel industry has always been known for its subtle alterations, but the existing global economic situation opens the door to several disruptive organizational changes. People can adjust to structural change productively and effectively with the aid of change management. Small to mid-sized enterprises in the Textile & Apparel industry confront an exclusive set of difficulties, including the need for the state of the art managerial skills, high investment requirements for new knowhows, arbitrage related to relocation that impacts labor costs, local industry protectionism, unstable purchaser preferences, and a requirement to rebalance the shift in managerial emphasis from functional to strategic and change management competence (Liviu, 2018). For modern managers working in the textile and clothing business, a framework for handling transitions combined with the corresponding execution discipline and focus on international market dynamics offers a requirement.

1.1 Industry Overview

Before the Industrial Revolution, producing textiles required effort and time. Hand spinning was required to transform raw materials like cotton, flax, and wool into yarn or thread. Fabrics were made by weavers on looms at home or in small workshops Today, we buy apparel, wear it a few times, and then throw it away. The fourth-largest manufacturing industry in the world is the creation, production, and distribution of apparel (Monet, 2022). In the era of Industry 4.0, Textile & Apparel businesses have recently experienced intense competition. The same issues, such as decreased lead times for orders and increased material costs and labor prices alongside smaller margin of profits, are being faced by all industry participants (Ahmad et al., 2020). Additionally, consumers, particularly those of gen Z, demonstrate environmental consciousness and are prepared to spend a premium for eco-friendly goods (Wood, 2022).

Enterprises are implementing the latest technology solutions to satisfy stakeholders' rising preferences for environmentally responsive besides being sustainable Textile & Apparel products ("Technology trends in the apparel industry | CBI", 2022). Therefore, as a result, in the era of 4IR, the Textile & Apparel (T&A) sector needs to operate more intelligently.

1.2 Justification of this Study

The textile & garment (T&A) industry is one of the fastest-growing businesses, employing millions of people (Singh, S., & Khajuria, R., 2018). The Textile & Apparel (T&A) trade is changing rapidly. The mobilization of the 4IR is transforming the industry value chain. Leveraging automation, artificial intelligence, 3d printers and

weaving, robots & smart manufacturing, virtual or augmented reality, etc., the Fourth Industrial Revolution is reshaping the traditional operating procedures of the garment business (Jin & Shin 2021). In addition, it is transforming the sector by implementing new customer preferences. The outbreak of Covid-19 had a profound effect on worldwide clothing supply systems. Global retailers and brands cancelled orders with their supplier factories, while several governments have imposed travel and assembling restrictions. Consequently, some clothing manufacturers halted production and fired or suspended their employees. The majority of the studies on the T&A industry were before the pandemic. The present scenario requires a post-pandemic review on the T&A industry.

1.3 Objective and Scope of the Study

The study explored the trends in the global Textile & Apparel industry and attempted to identify the reasons behind these trends and shifts. The global industry was experiencing changes after the Covid-19 pandemic, which played an instrumental role in the adoption of the fourth industrial revolution technologies. The main purpose of this study was to identify and explain specific industry trends, with a particular focus on the adoption of the 4IR technologies. The strategic insights derived from this review paper will be useful to the strategists, policymakers, and researchers in the field of the garments and apparel industry globally.

1.4 Methodology

This is a desk review article based on secondary data collected from multiple sources, including scholarly articles and credible web resources. This paper followed the structure and methods for creating a standard review article by running a systematic review of the global scenario of the Textile & Apparel industry. More specifically, the article reviewed the work of other researchers and summarized relevant literature with an objective to capture and explain the present state of knowledge on contemporary disruptions in the Textile & Apparel (T&A) industry caused by Covid-19 and Industry 4.0 technologies. It utilized recognized articles based on the global best practices from various journals. Apart from the journal articles, the paper further looked into the latest best practices and innovations from various credible news sites, business newsletters, expert blogs as well as academic video lectures.

2. Contemporary Global Shifts in the Apparel Industry

2.1 Changes in Consumers' Preference

In the global market, the competition is fiercer than ever, and it is harder to foresee consumer demand due to the internet and the stagnation of Western markets. Additionally, fashion retailers no longer have influences such as in establishing trends (McKinsey & Company,2021). Consumers are accustomed to observing brand engagement and mentions alongside exchange relationships between peers and influencers in social media, as well as on entertainment venues, in the majority of global marketplaces. Over half of the TikTok users in the United States have bought a brand's product or service after seeing it marketed, promoted, or reviewed on the site (Lundstrom, 2021). The global fashion sales share of e-commerce virtually doubled between 2018 and 2020 in some locations (The Business of Fashion and McKinsey, 2020).

Provided lifestyle and demographic patterns stay unchanged, the worldwide consumption of clothing will climb from 62 million tons in 2019 to 102 million tons in the next decade (World Bank, 2019). According to the World Bank (2019), from growth stage of cotton to the ready product that is finished and is delivered to the retailer, it uses 3,781 liters of water to manufacture a set of jeans. The same report says that by 2030, the emission of the harmful greenhouse gases from the fashion business will have increased above 50% continuing the present rate. A report by Mckinsey Apparel (2018) shows that purchasers are increasingly getting more conscious of the negative ecological effects of conventional line garment making methods, and overstock liquidation is a topic of growing public uproar. According to 78 percent of study participants of Mckinsey Apparel, sustainability would likely play a significant role in consumer decisions to buy mass-market clothes by 2025 (Andersson et al., 2018).

The willingness of consumers to champion and purchase products that are sustainable that are distinguished by pricing, service, and quality, has, to date, been the subject of a great deal of research on corporate sustainability. Industries are under increasing pressure from the industrial ecosystem, worldwide business trends for following sustainable practices, and the customer-centric economy to grow more sustainable, inventive, and adaptable. (Ahmad et al., 2020).

Many textile and apparel firms – such as H&M, Patagonia, and The North Face – are integrating sustainability into the supply chain as a top priority, and improving their compliance standard as it relates to sustainable supply chain management (Shen et al., 2017).

2.2 Digitalization as a Competitive Edge

The difficulties facing the modern supply chain continue to center on production transparency and efficiency.

Smooth interactions with suppliers through platforms or other digital links are essential because it's becoming more and more critical to be aware of the state of production and shipments regularly. To increase real-time production efficiency and quality, prominent suppliers are investing in semi-automation, artificial intelligence, and Industry 4.0, according to McKinsey's work with manufacturers in 2021. Surprisingly, 68 percent of survey participants said they intended to increase the number of suppliers who have these capabilities—an increase of 8% by more than a quarter (Hedrich et al., 2021).

2.3. Nearshoring Strategy

According to Andersson et al. (2018), to obtain a cost advantage, mass-market garment firms and merchants in Europe and the US hastened to relocate as much production to Asia two decades ago. Since then, a unit-cost play has become popular, with an emphasis on shifting from China to increasingly cost-effective frontier markets and altering the footprint of sourcing. Players in the apparel industry who have done this well have been able to provide consumers with pertinent products at competitive costs while maintaining ambitious standards for quality, timeliness, and compliance.

Today, the sector is at a juncture where speed trumps profit margin advantage and simple adherence is being enhanced to an inclusive sustainability plan (Andersson et al., 2018). The old supply chain structure is now being disrupted, and as labor costs consolidate, brands and retailers are beginning to reconsider their sourcing and manufacturing methods in a more comprehensive manner.

In Mckinsey's report (Andersson et al., 2018), the data shows that rather than offshoring in China, nearshoring in Mexico and Turkey can reduce cost in price in 2016-17 by 12 percent and 3 percent. Also, in China, the shipping days were 30 days. Whereas in Mexico it was 2 days and in Turkey, it was 3-6 days.

Before firms can completely comprehend the possibility of automation for garment production and its possible influence on nearshoring or onshoring, they must have a comprehensive awareness of the technology environment. Nonetheless, the memorandum is strong: Automation not only increases the desirability of nearshoring for European and American fashion retailers and brands but also renders onshoring to the United States commercially possible for specific products.

3. The Changing Fashion Cycle

There are two kinds of apparel needs, fashion needs and basic daily necessities (Rony, 2022). Both types have their strength and weakness. Basic need items consist of standard designs and are produced in bulk. They do not usually need diversification; manufacturers can sell them as raw materials to designer companies that are going to modify and sell those products. Demand for basic items is not affected by economic difficulties (Nickolas, 2022), but they may fall in the cheaper segment of the market. So, while basic apparel producers are mostly safe from economic difficulties, once sophisticated automation becomes widely adopted, they are going to lose their only comparative advantage "cheap labor" (fibre2fashion, 2020).

Fashion, on the other hand, is highly elastic to economic situations (Nickolas, 2022). Fashion can be of two types, such as, global fast fashion trend and stable traditional slow fashion (fibre2fashion, 2021). Suits, formal attires, casual attires local cultural items (e.g., sari and panjabi in Bangladesh/India context, yukata in Japan context) are stable traditional items, among them suits style change slowly, therefore can be diversified in terms of quality and variables like handcrafted/art, brand values, environment friendly, better wage, etc. Their demand is stable but susceptible to economic changes. The fast fashion trend is something else: it usually comes from trendsetter societies, lasts for a few weeks or months, and then is replaced by contemporary trends (Stanton, 2022). The trends may come back, but they are unpredictable and can't be capitalized on. Because of this, the demand for these products comes in small quantities, with limited time to complete them. So, unless a lead time is a strong point for manufacturers, they can't keep up with it. Thanks to global connectivity, fast fashion is on the rise.

Globally, fast fashion is on the rise. However, it is highly criticized for its extreme impact on the environment (Azevedo, 2018), low quality of products, and ethical complications like poor working conditions and low wages of workers (fibre2fashion, 2021). As the world is shifting towards eco-responsibility, affirmative actions, and human rights. Fast-fashion should therefore lose its traction too!

4. Apparel 4.0: Textile & Apparel Embracing Frontier Technologies

Mark Wieser first introduced the phrase "Industry 4.0" in 1991, and he intended to draw attention to "pervasive computing" (Chen & Xing, 2015). Industry 4.0 is distinguished by its emphasis on end-to-end communication, digitalization of the whole value chain, as well as horizontal and vertical integration. In the joint effort by Chen and Xing (2015) the authors have pointed out Internet of Things (IoT), Cyber-physical Systems (CPS), Enterprise Resource Planning (ERP), and Machine-to-Machine (M2M) Communication one of the few revolutionary technical frameworks that enable the visualization, personalization, and customization of the manufacturing process in Industry 4.0. When applied to the textile industry, Industry 4.0 promises to reduce

production costs while simultaneously fostering innovation and ecological responsibility in the goods consumers buy and use (Chen & Xing, 2015; M. M. Islam et al., 2020; Jin & Shin, 2021).

The largest issue, according to Chen and Xing (2015), is preparing the next era of employees and management to make the most of the opportunities presented by Textile 4.0. The absence of innovation in the textile industry was highlighted as a problem. This stands in sharp contrast to what is required by textile companies to discover, adopt, and continually refine technical paradigms that may save money, cut production times, lessen their impact on the environment, and increase value for their customers (Chen & Xing, 2015). As a result, Chen and Xing (2015) suggest that a suitable method for businesses in the textile sector to go ahead is to implement pilot projects that investigate technology possibilities on a modest scale while allowing people to improve technical skills, knowledge, and mindsets.

The human resource management techniques available in the era of Industry 4.0 are revolutionary. In an increasingly competitive global market for better quality products at cheaper rates, companies who can attract, retain, and train their employees will have a leg up. Effectively reaping the benefits of Industry 4.0 is also crucial. Automation, improved connection, and digitalization of already performed operations are all ways in which Industry 4.0 may help businesses save time and money. Small and medium-sized businesses in developing south Asian countries like Bangladesh, Vietnam, Cambodia, Laos, etc. also face serious dangers to their profits and business models as a result of automation (Rumi et al., 2021). Due to their reliance on low-cost labor, small and medium-sized enterprises in the export-oriented segments of RMG are utterly incapable of undergoing the expensive transformation process and changing into a high-productivity business model (Rumi et al., 2021). Since the nation employs a big number of foreign laborers from neighboring India and Sri Lanka, the lack of competent talent at the top levels of management translates into higher costs, more dependence on foreign capabilities, and inefficient managerial judgments (Rumi et al., 2021). Udayagani et al. (2019) showed how cloud computing and IoT technologies may help textile businesses in Bangladesh automate their manufacturing lines more effectively, although they face several challenges.

According to World Economic Forum (2018, January 11), export revenues, and job creation, emerging nations like Bangladesh, Vietnam, Cambodia, and Pakistan may benefit greatly from adopting 4IR technological paradigms. Value creation, competitive advantage, waste control, and efficiency are just some of the areas where 4IR technology may be put to use. Rather, 4IR technologies can be viewed as a paradigm shift that has the potential to impact every link in the value chain, from the initial stages of raw material production and transportation to the final stages of product packaging, transportation, maintenance, insurance, advertising, and a host of other ancillary services.

According to Ahmad et al. (2020), the textile sector may explore sustainability and value development thanks in large part to the use of business information. A competitive advantage for these textile companies can be found in business intelligence, which Ahmed et al., (2020) define as the ability to derive superior insights and decision-making capabilities from inputs collected across a variety of technological paradigms such as the Internet of Things (IoT), cloud computing, machine learning, robotics, big data, etc. In the context of shorter fashion cycles, for instance, business intelligence may help companies make more precise demand predictions, cutting down on waste and minimizing lead times. However, companies may anticipate consumer tastes throughout a fashion cycle with the use of forward-looking market sentiment monitoring and incorporate that information into their manufacturing processes at a quicker rate than their rivals. This group of technologies may help Bangladesh's textile industry overcome supply-side constraints (Chowdhury et al., 2018).

Comprehension of a myriad of data points accumulated to yield managerial decisions may hold the key to prolonged customer loyalty and commercial success in a rapidly evolving industry like textiles, where firms are susceptible to shifts in raw material prices, changes in customer desires and preferences, supply side pressure and cost competition, operational risks, and fashion cycles of progressively shorter lifespans (Ahmad et al., 2020).

The potential for the garment industry and apparel product manufacturing, in particular to save money and increase consumer happiness via the use of computer-aided design techniques and augmented reality in the manufacture and retailing farther down the supply chain is also substantial (Abtew et al., 2018; Cichocka et al., 2014; Liu et al., 2016; Zhu et al., 2018). While blockchain is garnering attention due to the rising value of digital currencies, it may have far-reaching effects on the textile industry. The ability to track the origin of finished goods down to their raw materials opens up a new door for ensuring product quality and winning over skeptical customers. Manufacturers in the textile industry can carve out new markets for one-of-a-kind and/or environmentally sustainable products by applying blockchain technology alongside alternative traceability schemes that let consumers track the origins of their materials and the quality of their finished goods (Bullón Pérez et al., 2020).

Of the 60 million people who work in the global clothing business, over 75 percent are womenfolk. A large number of women are employed in the garment industry, and female workers are overrepresented in the lowest-paying, most insecure jobs in the industry. The global clothing industry is feeling the effects of the COVID-19

pandemic. Prominent brands and retailers worldwide cancelled orders alongside their supply facilities, and several governments instituted travel and assembly prohibitions during the outbreak. As a result, a number of textile factories ceased operations and either lay off or halted their workforces. Many businesses also faced unprecedented challenges, such as disruptions in the supply chain, shortages of available labor, and fluctuations in customer demand (Sutcliffe, J., 2021).

Remarkably, the recent pandemic has pushed industrial firms into the 4IR faster than predicted irrespective of their readiness. Companies had to quickly adjust to a highly remote environment in order to assure continuation and safety as quarantines drove the world toward internet platforms. McKinsey & Company found the majority of large businesses adopted 4IR technologies on technology as a result of the COVID-19 pandemic. These businesses anticipated that this significant shift in the usage of 4IR technology was highly likely to remain in place long after the pandemic had ended. The focus of companies moved to develop technology and tools to facilitate their operations in ways and at rates that were previously unthinkable. Businesses that have embraced this acceleration will be in a strong position as we move past the pandemic and into the opportunities and challenges of the future (CPA, G. F. R., 2022). Ready Made Garments (RMG) businesses around the developing parts of the world also had to adapt faster with the inclusion of 4IR in their production and supply chain. As a result of the COVID-19 outbreak, nearly every nation instituted a nationwide lockdown to minimize the spread of the disease and ensure social separation. The prolonged government shutdown taught businesses everywhere that conventional methods of in-person collaboration and communication simply won't cut it during the pandemic. In time, even if reluctantly, most of these businesses shut down their brick-and-mortar locations in favor of remote workers. This accelerated transformation is reflected both in corporate management and in the manufacturing process (Naim, S. J., 2021).

The results of a recent McKinsey survey (Agrawal et al., 2021) suggest three possible outcomes: success for businesses that have already implemented large-scale digital technology deployments; caution for those still in the scaling phase; and a call to action for those who have yet to embark on their Industry 4.0 journeys. With Mckinsey's annual 4IR survey of worldwide manufacturing corporations, they have been keeping tabs on the development of the fourth industrial revolution since 2017. Six months into the global coronavirus outbreak, their most current poll of over 400 firms gives a picture of the viewpoints of CEOs. More than half (56%) of those surveyed stated Industry 4.0 technologies were crucial to their crisis responses, and 94% said they had aided them retain maneuvers operating throughout the catastrophe.

The survey showed that even before COVID-19, one Asian CPG firm had created a digital duplicate of its supply chain. During the pandemic, it used to simulate a variety of possible futures, including shutdowns of production facilities and shortages of raw materials. A North American PPE company that was expanding production by installing a new production line used augmented reality-based remote help for project execution to get the line-up and running from halfway across the world (Agrawal et al., 2021). According to the same study, lack of funding is considered the biggest constraint to the implementation of 4IR technologies in the apparel business. The second major challenge was a limited understanding of technology and vendor landscape, while a lack of people, skills and knowledge were the third.

The remaining part of this section provides an overview of how 4IR knowhows—robotics and smart manufacturing, 3D kitting and printing, virtual and augmented reality, and artificial intelligence—are being applied in the apparel industry.

4.1. Smart Clothes

Under this technology materials and electronics are incorporated directly into the fibers of smart clothing. Three types of smart textiles; Active, Passive, and Ultra-Smart (Ajmera, 2021) are visible in practice. Passive ones are just woven with special materials for specific situations. For example, UV protective clothing, multilayer yarn, plasma-treated cloths, conductive fibers, ceramic coated fabrics, and optical fiber-woven fabrics.

Active ones on the other hand come with sensors and actuators. Clothes with shape memory, chameleonic abilities, suits with water resistance, heat storage, and thermal regulation are all active smart clothes. finally, ultra-smart textiles are products that react to the environment or stimuli. Space suits can be considered the best example of that, headcap used for neurological analysis is an example of computing clothes and data wears (Ajmera, 2021).

Smart clothes have medical applications in many fields. They are used in medical fields textile sutures, psych monitoring, or tissue engineering. In the military, we see experimental camouflage – 'Auxetic Materials'. In scientific research and utilities thermal sensitive materials, intelligent membranes, and chemically responsive materials are used. Smart clothes have immense potential in fashion wear due to the rise of the cyberpunk fashion genre (Zoller, 2021).

4.2 3D printing and 3D knitting

3D printing is an additive process. In this process, production is done by combining consecutive layers of

materials, known as filaments, and items are made. The ability to produce in small quantities or on demand helps businesses to significantly reduce their surplus inventory (Friedman, 2019; Tailored Industry, n.d.). Without the need for stitching, 3D knitting employs needles to create knit goods in one piece. (Miodownik, 2015). 3D printing and 3D knitting can also boost productivity and hyper-personalization. By eliminating human labor and streamlining the production process, this technology reduces left-over, lead time, and manufacturing costs. Hyper-personalization, which is expensive to scale using traditional methods, is made possible through lean operations and digitalization. (Paul, 2001).

4.3 Virtual and augmented reality

With the use of virtual reality (VR) technology, the user's actual surroundings are replaced by a digital environment that is created by a computer. A real-world environment can be replicated or rendered in an entirely artificial environment (Kunkel, 2016). 'The Digital Twins' technique is one tactical digitalization strategy. Production and manufacturing procedures supposedly be duplicated on a digital podium in a virtualized setting using digital twins (Halenar et al., 2019).

4.4 Artificial intelligence

Machines that replicate cognitive processes such as pattern recognition, perception, and learning are referred to as artificially intelligent (AI) systems. Brands may make educated decisions about their products, marketing, and pricing by examining real-time retail data on their rivals' items, prices, and promotional messaging. Additionally, AI may support in scrutinizing consumer interests and procuring patterns as well as automatically correcting inventory contingent on current demand. AI can propose the appropriate sizes to consumers based on specific clothing specs and stylistic characteristics. Based on prior purchase history, client preferences, and comments, it may also make recommendations for products that are catered to specific tastes. AI is also capable of examining the characteristics of top-selling products to produce fresh designs that have the best chance of succeeding as bestsellers (Delcea, 2022).

4.5 M2M communication

The automatic data transfer and measurement between mechanical or electrical devices are done via machine-to-machine (M2M) connections. With the ability to convey production data and identify issues with the machine or potential problems based on the pertinent KPIs, knitting machines have entered the next stage of their growth. Some players have even gone so far as to create cutting-edge fixes to anticipate the problems and address them (Apparel Resources (Ed.)., 2020)

4.6 Vertical and Horizontal Integration

Vertical integration for Industry 4.0 entails linking all organizational departments and workflows. in other words, vertical integration is combining enterprise-level information technology (IT) with operational technology (OT) at the production level. Data is shared and made accessible to all business divisions thanks to this connection. The production ground, promotion, transactions, after-sales service, purchasing, accounting, Human Resource, quality control, research wing, and other areas are included in this (MAG, 2019).

Horizontal integration covers the manufacturing facilities, multi-site operations, and downstream and upstream third-party partners in the supply chain (MAG, 2019). The goal of horizontal integration inside any manufacturing plant is to create a "Smart Factory" where all equipment, processes, and systems are interconnected and constantly communicate. Horizontal integration ensures maximum visibility, production flexibility, and cooperation across multi-site operations by delivering the same degree of connection.

4.7 Blockchain

At every stage of the industrial value chain, from the procurement of raw materials to the shipment of the finished product, blockchain can boost transparency and trust. A number of common issues related to compliance that are faced in supply management can be resolved with blockchain technology (Sorensen et al., 2019). Further usage includes supply chain monitoring for increased transparency, the provenance of the materials, and the identification of fakes, regulatory compliance, identity management, asset monitoring, and engineering design for long-lasting, complicated goods.

4.8 Smart Factories

The processing and analysis of data in real-time from web-based IoT sensors and gadgets allow a fully integrated smart industrial unit to provide an exactly accurate picture of production activities. Possibilities like analytics, self-assessments, repair, and self-optimization are possible in a networked plant. For example, Hugo Boss factories in Turkey make use of 'Smart data management' to provide access to data and keep employees efficient, they also make use of AR/VR to train employees (Sarkar, 2020). AI-based quality-checking systems and

Robotics are also used alongside traditional manpower.

Table 1: Global Practices of Various Technologies and Innovations

Countries	3rd IR Automation	4th IR Automation	3D Manufacturing	Trendsetter	Trend follower	Biotechnology	Complete Integration – Smart Factory
USA	Yes	Yes	Yes	No	Yes	Yes	Yes
Germany	Yes	Yes	Yes	No	Yes	Yes	No
Japan	Yes	Yes	Yes	Yes	No	Yes	No
Korea	Yes	No	Yes	Yes	No	No	No
Turkey	Yes	No	Yes	No	Yes	No	No
China	Yes	No	Yes	No	Yes	No	No
Vietnam	Yes	No	No	No	Yes	No	No
Pakistan	Yes	No	No	No	Yes	No	No
India	Yes	No	No	No	Yes	No	No
Bangladesh	Yes	No	No	No	Yes	No	No

Sources: Ajmera, 2021, Apparel Resources, 2020, Delcea, 2022, Francis, 2019, Kiron, M.I., 2021, Rasheed, Zafar & Ed., 2020, Tracy et al., 2016, Varshney, 2021, Vlog, 2019, Yarn Spinning, 2011, Zoller, 2021, Friedman, 2019; Tailored Industry, n.d., Miodownik, 2015, Paul, 2001, Kunkel, 2016, MAG, 2019, Sarkar, 2020

As shown in Table 1, USA, Germany, and Japan are the technological pioneers of textile garments and research. However, it needs to take note of that none of these countries are on the list of the top exporters of the T&A products. China is the biggest exporter of textile goods followed by Bangladesh (Mirdha, 2018). In a number of industries, including textiles, clothing, household appliances, electronics, food, and pharmaceutical, the Chinese government intends to sponsor 200 demonstration smart manufacturing units (Fibre2Fashion News Desk (Ed.), 2022).

5. Apparel 4.0 Plus: Emerging Role of Biotechnology in Textile & Apparel

A growing number of innovative firms, across the globe, are working to incorporate sustainable alternatives in the textile industry to reduce carbon emissions and other harmful environmental impacts while maintaining or as in some cases, outperforming existing performance benchmarks. These innovations hold enormous potential for textile firms across the market segments. Biotechnological innovations have great potential to transform the textile industry in the coming decade. Some of the areas where the industry has made encouraging progress include alternative sources of fabric that retain or sometimes excel in performance benchmarks e.g., spider silk, mushroom leather, and mycelium-based foams. Reduction of water usage by using materials derived from microbial cellulose. There are currently many advanced dying processes driven by microorganisms such as bacteria, and yeast do not require the use of corrosive and toxic chemical agents currently being used for coloring, in the industry (Chimileski, 2017).

Table 2 summarizes a list of companies operating in various countries with promising biotech innovations that can change how textiles are manufactured, treated, and maintained. At the same time, the companies in this list also have plans to transform other segments of the apparel and fashion industry, including leather goods and outdoor wear.

Table 2: List of Biotechnology Firms and Their Innovations

Company	**Founded in**	**Country**	**Primary product**	**Fiber/Dye**	**Product stage**
Bolt Threads	2009	USA	MicroSilk, Mylo	SpiderSilk Protein, Mycelium	Prototypes Completed
Spiber	2007	Japan	Brewed Protein	SpiderSilk Protein	Launched
AMsilk	2008	Germany	BioSteel	SpiderSilk Protein	Launched
Algalife	2016	Germany	Fibre and Dye	Algae	Launched
Algiknit	2017	USA	Yarns	Kelp	Developmental
nanollose	2014	Australia	Nullarbor	Microbial Cellulose	Launched
P	2015	France	Dye	Micro-organism Engineering	Launched
Colorifix	2016	UK	Dye	Engineered Bacteria	Launched

Source: Ramsay (2020)

5.1 Three Distinct Biotech Innovations with Tremendous Scope for Transformation

Out of an increasing number of innovations and areas of biotech discovery, three core areas of innovation hold immense potential. In this section, these three have been briefly discussed (McCarty, 2022).

Engineering Proteins for Stronger Materials

Genetic tweaking of protein structures can yield structures like spider silk that are five times stronger than steel

due to their makeup of thousands of nano-strands (Miceli, 2018). 'Spiber Inc.' has found a way to produce spider silk without having to farm spiders through the fermentation process (McCarty, 2022). Applications of this fiber can be a "game-changer for many outdoor applications". Spiber Inc. has already partnered with 'The North Face' to produce high-performance ski jackets made out of spider silk (McCarty, 2022).

Molecular Assembly

The root structure of mushrooms, called mycelium, can be assembled to produce complex materials (McCarty, 2022). 'Ecovative Design', a company founded in 2007, is producing millions of pounds of mycelium-based products for industrial customers that proves its economic viability. MycoFlex is one of their most promising products. It is produced from a "mycelium-based foam" (McCarty, 2022). Their data shows that the foam exhibits considerable flexibility and tensile strength against bending before reaching the rupture point.

Material Production through Algae

The textile industry uses oil and oil-based products in manufacturing fabrics and adding layers on top of manufactured products. This process is energy intensive. On the other hand, a California-based company named Checkerspot, has found a way to produce oil through synthetic and organic chemical engineering of algae. Importantly, their product is already proven to be applicable at scales as high as 625 cubic meters (McCarty, 2022). At the same time, the company is working with producers to create a bio-based "hydrophobic" coating that is free from fluorine, which is applicable for use on "apparel, cookware and yoga pants" as well as outdoors sports-wear (McCarty, 2022).

6. Conclusion

This study researched and explored how the Textile & Apparel industry is embracing changes due to the fourth industrial revolution technologies, fast-evolving consumers preferences, sustainability concerns, nearshoring trends, and diminishing product life cycle. Many developed nations had their industrialization process started with textiles. With globalization, the industry slowly moved to developing countries. This article reviewed how industrial and technological advancements impacted manufacturing and other business processes over time. Once a labor-intensive industry, the textile, and apparel industry is now getting increasingly reliant on machines. 4IR technological progress has allowed a significant increase in productivity, but at the cost of jobs. with the advent of automation and 4IR technologies, the future of Textile & Apparel industry jobs is likely to shrink and transform faster than expected. However, developing countries to a large extent are still reliant on human capital as their key factor of production. The big question remains, "*in this post-pandemic 4IR era, is the Textile & Apparel industry destined to return, like a migratory bird, to its original home (i.e., the industrialized countries with developed economy), or to settle in emerging economies having the capability of transforming themselves?"* While exploring this, future research endeavors should also determine how the current tendencies blend or conflict with one another. It would be valuable, to investigate potential conflicts, for instance, between hyper-personalization and environmental sustainability, productivity and job creation, and the like.

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