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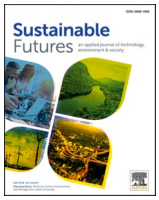

Sustainable fashion transition towards net-zero future: A review of digital and material innovations, policies and regulatory framework

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ABSTRACT

The fashion industry has long been linked to complex social and environmental issues like labour exploitation, resource depletion, and carbon emissions. In alignment with the Sustainable Development Goals (SDGs) 8, 12, 13, and 15, various sustainable fashion initiatives have emerged to mitigate the industry's impact on the economy, society, and the environment. While there has been extensive research on sustainable fashion, there are limited studies that simultaneously investigate the geospatial collaborative networks alongside a comprehensive systematic review of the digital and material innovations, policies, and regulatory frameworks that facilitate the transition to a net-zero future. This integrative systematic review critically examines the advancements in sustainable fashion transition towards net-zero over the last two decades. It was found that recent efforts in digital, materials, and process innovations, along with the enforcement of existing policies and regulatory interventions are accelerating the transition towards net-zero for the achievement of the "Fashion Pact 2050". The findings suggest that collaboration and partnerships are essential for advancing sustainable fashion, as they enable fashion brands, NGOs, and governmental entities to unite their diverse expertise to drive innovation and share best practices. Such collective efforts enhance the impact of sustainability initiatives, fostering a more effective transition toward a net-zero future in the industry. This article further provides practical recommendations and implications for industry, academia, and governments for accelerating the transition to net-zero fashion; making it a useful material for researchers, fashion businesses, funding organizations, and policymakers.

1. Introduction

The fashion and textile sector is considered to be one of the world's most polluting industries - surpassed only by the oil and gas sector [1]. This pollution can be attributed to the extensive use of energy, water, and chemicals during production along with the associated carbon emissions [1,2]. As the global awareness of climate change intensifies, stakeholders across the apparel sector are increasingly recognizing the importance of sustainability not merely as a trend, but as a fundamental necessity for reducing the industry's carbon footprint. The global net--zero' (GNZ) 2050 and the UNDP SGDs 2030 goals [3–5] are central to the call for climate action. Consistent with these calls, the "Fashion Pact 2050" was signed at the G7 Summit in Biarritz, France, in August 2019 [6]. This initiative was launched by a coalition of fashion companies aimed at promoting sustainability and addressing climate change, biodiversity loss, reducing carbon footprint and ocean protection within the fashion industry [7]. This has led to fashion industries adopting strategies to herald this global transition. This transition represents a critical milestone in the global effort to mitigate climate change and reduce the environmental footprint of human activities [8,9]. Such a paradigm shift requires a holistic rethinking of the entire fashion value chain from raw materials production, sourcing, design and production, distribution, and consumption[10].

In the past decade, businesses and organizations have significantly invested in sustainable initiatives and innovations, including substantial funding for digital technologies, material innovations, enhancing customer awareness, enforcing sustainable policies, and developing industry and regulatory frameworks (see Fig. 1) [10,11]. The "Cradle to

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Cradle" strategy is a socio-technology innovation strategy that aims to reduce waste by designing items with the intention of recycling or composting them at the end of their lives [12]. Also in focus are the efforts to maximize energy efficiency in production processes and the shift to renewable energy with the ultimate aim of eliminating fossil fuel from textile manufacturing and reducing carbon footprint [13–15].

Technological innovations are essential components in the journey towards net-zero emissions [16,17]. Digital innovations such as 3D printing, digital design tools, IoT, robotics and advanced manufacturing processes are driving sustainable innovation in the fashion industry leading to reduced energy consumption and less waste generation [18–20]. Typical technologies like Product Lifecycle Management Systems (PLMs) enable better traceability of materials and products, ensuring ethical sourcing and production practices. This technology also ensures transparency in supply chains, which is crucial for promoting sustainability and accountability within the fashion industry.

Strategies for consumer inclusion in the transition to net-zero future fashion are essential for holistic solution transition [21]. Similarly, policies and regulations play a significant role in shaping the sustainable fashion drive [22]. Studies on policy development and industry standards provide valuable insights into creating a supportive regulatory environment for sustainable fashion practices [23]. Governments and international organizations are increasingly implementing policies aimed at reducing the environmental impact of the fashion industry [22]. These regulations serve as both a catalyst for innovation and a guiding force for ethical practices, ensuring that sustainability becomes ingrained in the very fabric of fashion. While these efforts continue to shape the fashion industry's transition to a greener future, the needed results can only be achieved through multifaceted strategies that prioritize circular economy principles [24] and emphasize digitally enabled manufacturing processes [25,26]. These developments minimize waste and resource consumption while empowering consumers to make more informed choices. However, the integration of these innovations into established practices requires a concerted effort from all stakeholders, including designers, manufacturers, and policymakers.

While recent efforts have led to a significant expansion in the body of literature on sustainable fashion, there appears to be a considerable void in understanding how these innovations interact with existing regulatory frameworks and the degree to which they may facilitate a smooth transition to net-zero emissions. While many studies highlight individual technological innovations [17,27,28], policy initiatives [29,30], and circular economy initiatives [24,31], only a few studies provide a comprehensive analysis of their interconnections and cumulative impact on how the fashion industry can successfully navigate the net-zero transition. As the industry takes steps to transition to net-zero, it is important to understand the geospatial research collaborative networks and examine the role of digital and materials innovations, policy, and regulatory framework in this transition.

The purpose of this study is to conduct a comprehensive review of the current landscape of sustainable fashion, focusing on the role of digital and material innovations in facilitating the transition towards net-zero emissions. This review systematically analyzes existing literature, policies, and regulatory frameworks to elucidate the interconnections between technological advancements and regulatory support and provide actionable insights and recommendations for stakeholders within the fashion industry, policymakers, and researchers, fostering a collaborative approach to achieving sustainability goals in the fashion sector. To that end, this review seeks to answer the following research questions: RQ1. What are the digital innovations driving net-zero future fashion? RQ2. What are the materials and process innovations driving net-zero future fashion? RQ3. What are the consumer and social innovative drives propelling net-zero future fashion? RQ4. What are the existing policies and regulatory frameworks and their impact on the transition to net-zero future fashion?

2. Methodology

The bibliometric data for the systematic review was obtained from the Scopus database (SDB) using the enhanced PRISMA guideline [32]. This approach enabled a systematic retrospective evaluation of the research in sustainable fashion over the last 20 years. Thus, to provide a thorough picture of the sustainable fashion conundrum, an integrative systematic qualitative analysis was done based on the themes developed from the documents. The choice of SDB is due to its enhanced data categorization features, wider, and up-to-date content coverage, individualized author and institutional profiling, as well as its serial source profiles and interconnected database interface [33]. To obtain a thorough understanding of the field, other commercial databases and fashion new portals (details shown in Fig. 2) were explored to provide a balanced discussion on this important transition.

2.1. Search strategy

The systematic literature search was conducted on 30th March 2024 using the procedure illustrated in Fig. 2. The search strings were "sustainable* fashion OR sustainable* textiles", "sustainable* fashion

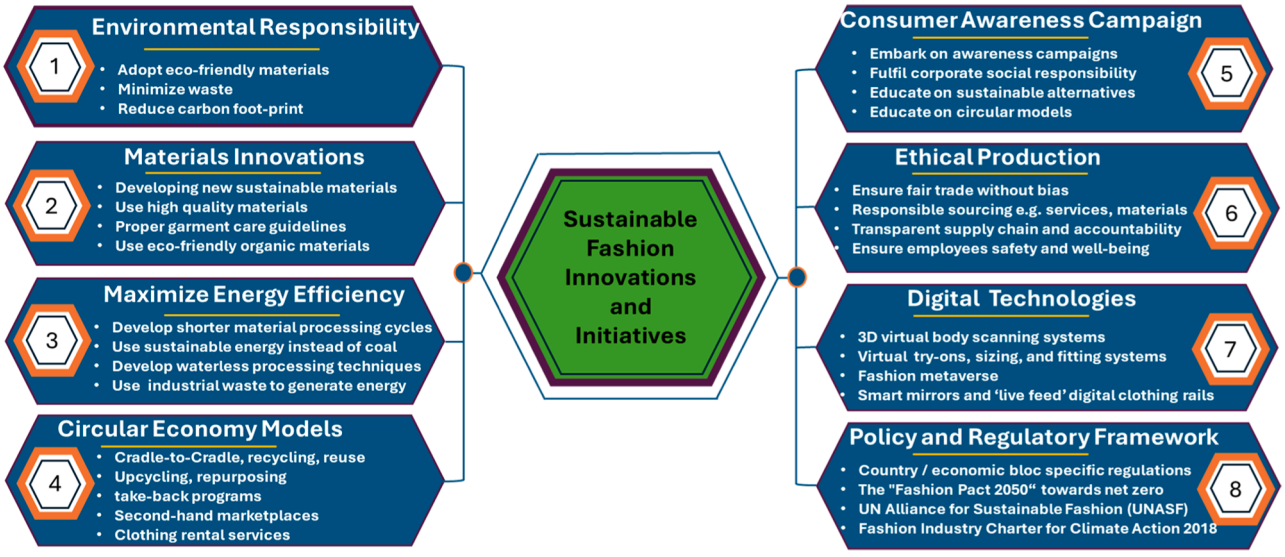

Fig. 1. Sustainable fashion innovations and initiatives.

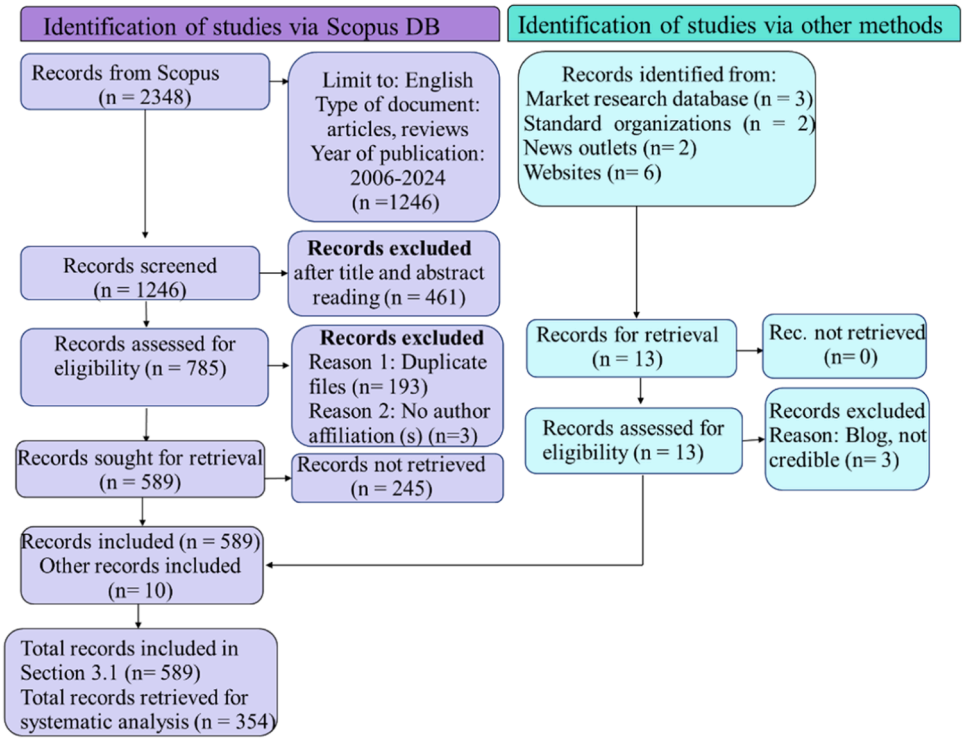

Fig. 2. PRISMA 2020 framework for records retrieval from databases.

sourcing", "sustainable* textile production", "sustainable* fashion materials", "sustainable* fashion business", "sustainable* clothing*" and "net-zero fashion". The search string results are shown in Table 1.

2.2. Inclusion and exclusion criteria

To exclude irrelevant items, data refining tools were employed. From the "document type" drop-down option, only "articles" and "review" were chosen. Additionally, the "language" option was limited to "English," while the "source type" option was limited to "journal." The publication year was limited to 2006 – 2024 to understand the publication trend over the last twenty years (see details in Fig. 2). The final documents were sorted in MS Excel after being downloaded as Comma Separated Values (CSV).

Table 1
Searched string used in SDB and resultant documents as of March 30, 2024.

S/N	Searched string	Total documents result	Documents results after applying filters	Documents after abstract and title reading	Documents after removing duplicates
1.	Sustainable* fashion OR Sustainable* textiles	1329	759	480	335
2.	Sustainable* fashion sourcing	37	17	12	12
3.	Sustainable* textile production	34	10	9	9
4.	Sustainable* fashion materials	801	435	172	133
5.	Sustainable* fashion business	14	8	8	8
6.	Sustainable* clothing*	133	96	91	74
7.	Net-zero fashion	105	34	18	18
				Total	**589**

2.3. Quality assessment of literature

As part of the quality assessment, titles, abstracts, and conclusions of the articles were thoroughly examined independently by three authors to ensure they covered the subject matter overtly. In instances of disagreement about the inclusion of a document, the team discussed and reached a consensus. Articles downloaded from other websites (see Fig. 2) were also examined and blog posts without references and editors were removed. To avoid duplication, screening of the article titles was done in MS Excel using the sort and filter option before analysis. To ensure accuracy in the information presented articles with no author names, affiliations, or journal names were further removed. For the thematic analysis, files that could not be retrieved (downloaded) were exempted leaving a total of 238 documents. The files obtained from other sources shown in Fig. 2 were only included in the content analysis.

2.4. Evidence extraction and data analysis

To extract the evidence from the documents, the bibliometrics software, VOSviewer developed by Nees Jan van Eck and Ludo Waltman [34], and Biblioshiny in R studio [35] for scientific mapping and visualizations were used. For part 3.1 under descriptive evolution of research, the entire bibliometric data made up of 589 was used. For the evidence extraction under the thematic analysis, 238 retrieved documents were analysed (See Fig. 3 for details) similar to the previous study [36]. VOSviewer (version: 1.6.20) and, in some cases, Biblioshiny software was used to generate the themes and social network clusters based on the keyword plus analysis.

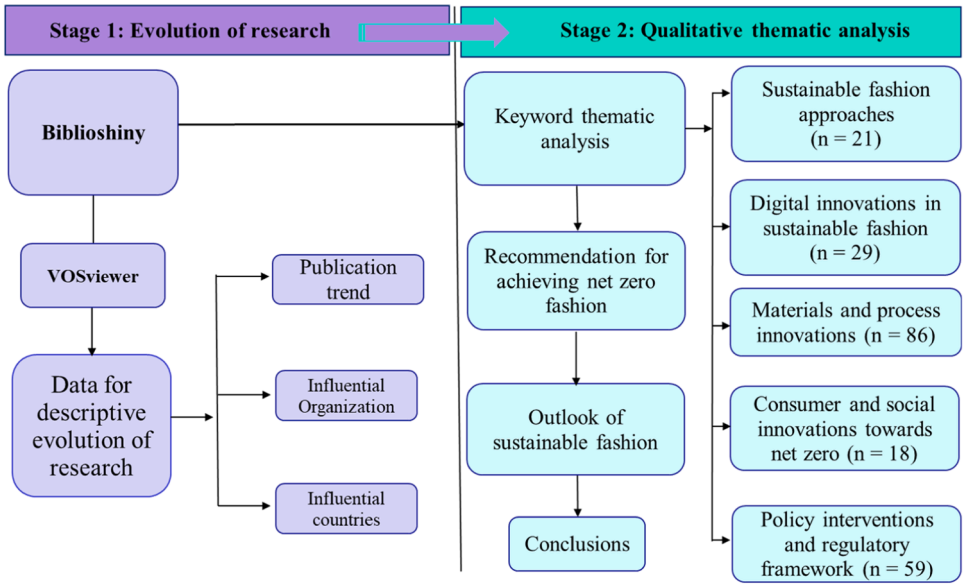

Fig. 3. Evidence extraction and data analysis procedure.

3. Results and discussion

3.1. Evolution of research

An examination of the annual publication trend shows a noteworthy output of scholarly works over the first two decades. Notably, 20 publications were made between 2006 and 2011, designating this period as an emerging phase. Since then, there has been a steady rise in publications from 2012 to 2016 (a total of 149 publications), denoting the "pick-up and pace" phase in sustainable fashion research followed by an exponential rise ($R^2 = 0.6132$) in the overall number of publications from 2017 to 2023, which suggests that sustainable fashion research was fast expanding in different research institutions around the globe compared to the previous years. This development may have been impacted by the "United Nations (UN) Sustainable Development Goals (SDGs) Agenda 2030", and the increasing consumer campaigns and advocates on sustainable fashion. These developments coupled with the new product label regulations in many countries have shifted fashion product consumption towards a more greener alternative, thus feeding into the circular economy model. To track the evolution of organizations' research output, the affiliations production over time was visualized. As shown in Fig. 4b, Yonsei University, Donghua University, and Aalto University have been at the forefront of sustainability research for quite a long time with an exponential increase in research output since 2015. Presently, fund allocations are geared towards sustainability issues, hence, there's bound to be an enormous rise in research output in sustainable fashion in the years ahead to 2030. This is estimated to propel the agenda towards attaining a green world. The highly cited countries/regions in the world indicate a strong scientific impact.

As shown in Fig. 4c, the United States is the major contributor to sustainability research in fashion and serves as the collaborative powerhouse to most countries, with significant collaboration between the United Kingdom and China. Country and regional collaborations are critical to expanding the frontiers of sustainable fashion research towards the achievement of net-zero targets.

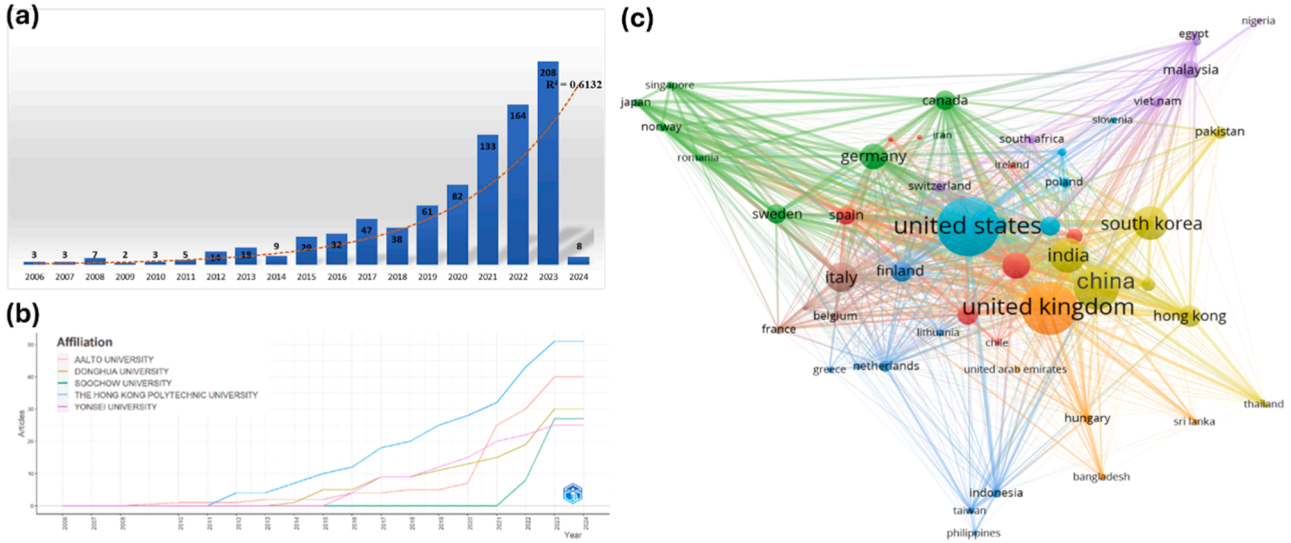

Fig. 4. (a) Annual global publication trend (b) Affiliation production over time, (c) Network visualization of influential countries in sustainable fashion.

4. Major themes in sustainable fashion transition to net-zero

Out of the accessible documents, the themes in sustainable fashion transition towards net-zero future fashion were consolidated into five major key topical themes comprising (i) sustainable fashion approaches, (ii) digital technologies in sustainable fashion, (iii) materials and process innovations, (iv) consumer and social innovations (v) policies and regulatory framework. A thorough examination of the documents under each theme provided insight into the transition towards net-zero future fashion from which recommendations were made for an accelerated transition.

4.1. Sustainable fashion approaches

The fashion business has expanded steadily throughout the years, outpacing other sectors in size as one of the global economies with an anticipated global revenue expected to exceed $2 trillion by 2025 from an estimated $1.5 trillion in 2021 [37,47]. Clothing unlike most products is ubiquitous and typically has a shorter lifespan because of the overconsumption culture that fast fashion has fostered over the years [38–40]. As noted by Cosscieme et al., [41], the production of garments generates all forms of waste amidst fair trade and labour issues. According to Mukherjee Sudeshna [42], the fashion industry uses the second-most water resources worldwide with 10 % of carbon emissions, and 20 % of wastewater as well as high energy consumption. For instance, to create one t-shirt and a pair of pants, 20,000 L of water, 24 % insecticides, and 11 % pesticides are used in the cotton production process [43]. Thus, the fashion industry's effects on society and the environment have received a lot of criticism in recent years [44]. As a result, the industry is at a crossroads to adapt its business models and production processes to align with the moral rights and the environmental appeals of society [37,42]. Based on these alignments, many brands have embraced recycling and upcycling practices to minimize waste and extend the lifespan of garments [45]. These practices help reduce the reliance on virgin resources and decrease the amount of clothing sent to landfills. Another area of concern in recent years is the exploitative labour practices within the fashion value chain. To address this, there has been a growing emphasis on fair trade and ethical labour standards. In recent years, the slow fashion movement has also acquired substantial traction as a protest to the industry's fast-paced, disposable nature [46]. This movement urges consumers to purchase fewer, well-made, long-lasting clothes. Slow fashion encourages a move away from the "throwaway" culture and toward a more sustainable, long-term approach to fashion consumption by emphasizing timeless designs, durability, and craftsmanship.

Beyond these ideas, buyers are calling for more openness about the sources and manufacturing methods of the apparel they buy resulting in the introduction of digital passports in Europe and other economic blocs [19]. Additionally, the fashion industry is witnessing collaborations and partnerships between brands, designers, and organizations to drive circular economy initiatives [47] in Fig. 5. These programs, which include clothing rental, repair services, and take-back programs, are designed to extend the life of materials and products. Such programs support a more circular approach to fashion, foster resource efficiency, and lessen waste. Though the industry still has a long way to go, the current sustainable fashion movement has seen significant growth [48]. Lately, most luxury brands have put sustainability first in meeting customer demands [49] by switching from the traditional methods of obtaining raw materials to more environmentally friendly alternatives [50]. For instance, top fashion manufacturers like Schoeller Textil AG and Flex apparel, as well as many fashion brands like the Swedish retailer H&M, the American seller of outdoor gear, Patagonia, and the French retailer Louis Vuitton, have all embraced a variety of green technologies [51]. Additionally, physical luxury retail stores have demonstrated admirable attempts to integrate green technologies into their supply chains and operations by utilizing low-impact materials, investing in renewable energy sources, and implementing waste reduction strategies [52,53]. Although the fashion industry in recent times placed a high priority on sustainability, it still thrives on consumerism, hence an unprecedented collaboration amongst all stakeholders will be required to radically shift the existing paradigm towards net-zero future fashion [54].

4.2. Digital technologies in sustainable fashion

Beyond the traditional sustainability models, most fashion brands have embraced digital technologies as a way of mitigating the environmental impact of traditional fashion and its associated impact [55,56]. Some typical examples include virtual showrooms, digital fashion experiences, augmented reality try-on options, virtual fashion shows, etc., (see Fig. 6). These digital innovations reduce the need for physical samples and travel, thus contributing to lessening the carbon footprint. Typically, in the case of virtual showrooms and digital fashion weeks, rather than organizing physical fashion shows and showrooms that require extensive energy consumption, travel, and infrastructure, brands are leveraging virtual showrooms and digital fashion weeks [57]. Designers no longer need to physically attend events in person to present their collections to a worldwide audience thanks to these internet channels [57,58]. This trend is consistent with the findings of Silvestri Barbara [59] indicating that virtual showrooms have the potential to offer interactive experiences that allow buyers and customers to virtually browse collections, examine comprehensive product information, and even use augmented reality (AR) technology to try on virtual garments. Beyond the virtual showrooms, Kim Jiyeon, and Sandra Forsythe [60], advanced that virtual fitting, for instance, has enhanced the online shopping experience, thereby reducing the need for multiple size

Fig. 5. Circular economy initiatives.

Fig. 6. Current digital technologies in sustainable fashion.

variations and minimizing returns as well as reducing the need for travels. Similarly, digital prototyping, virtual fittings using body scanning, and 3D design tools are making design faster, more flexible, and less wasteful by enabling designers to digitally develop and test clothing on virtual avatars before generating actual prototypes [61,62]. Prototypes are lately produced using additive manufacturing, which reduces waste and creates seamless design and product innovation.

Another important, although not so new technique is the use of digital lookbooks and catalogues instead of the traditionally printed and distributed lookbooks and catalogues [63]. Different brands create digital versions that can be accessed online or through mobile applications. Digital lookbooks can be created to be interactive, which allows for easy updates and customization [64]. From a sustainability perspective, digital lookbooks reduce environmental impact by eliminating paper production, printing, and physical distribution contributing to reducing the overall reduction of the carbon footprint of the fashion industry. The flexibility to make updates and distribute content easily allows brands to stay current and reach a wider audience. The interactive features create engaging and immersive experiences, while the global reach and accessibility transcend geographical boundaries [65]. Digital lookbooks and catalogues enable fashion brands to showcase their collections in a more sustainable, engaging, and accessible manner, while also reaping the benefits of improved efficiency and enhanced customer engagement, and at the same time helping accelerate the transition to net-zero future consistent with the fashion pact 2050 [65].

Online retail and e-commerce have revolutionized the way fashion is bought and sold lately. Almost all brands have online retail platforms and e-commerce websites, which reduces the need for physical stores and the associated energy consumption, waste generation, and transportation emissions [66]. Beyond the advantages of online retail platforms and e-commerce websites, this mode of fashion retailing also enables brands to reach a wider audience and personalize the shopping experience, reducing the likelihood of overproduction and excess inventory helping to promote sustainability [67]. Another important digital fashion sustainability technique is live streaming and video content. Live streaming fashion events, runway shows, and presentations enable viewers worldwide to experience the event in real-time without the need for travel thereby helping reduce carbon emissions [68]. Lately, brands have created high-quality video content that showcases their collections, behind-the-scenes footage, and interviews with designers, reducing the need for physical attendance and its associated carbon emissions.

In recent years, the advancement in digital communication and collaboration tools has enabled seamless communication and collaboration among designers, suppliers, and stakeholders [69]. Remote collaboration is made easier by technologies like cloud-based platforms, project management software, and video conferencing, which lessen the need for travel and in-person meetings, both of which increase carbon emissions [70]. Similarly, data analytics and sustainability reporting tools like product life cycle management have pervasive helping brands to collect, analyse, and report data on their sustainability performance over time. These tools enable real-time tracking and measuring of key environmental metrics helping identify areas for continuous improvement, set new targets, and communicate sustainability efforts transparently to all stakeholders [71].

The garment industry's efforts to achieve net-zero emissions have been significantly transformed by artificial intelligence [28]. AI technologies are being leveraged by fashion brands and businesses to optimize various aspects of industry operations, including manufacturing, materials, supply chain, and circular economy practices [28,72]. These advancements have had and will continue to have a significant impact on sustainability, which will pave the way for a more eco-friendly and responsible fashion industry. In the area of manufacturing, AI has revolutionized the manufacturing process in the fashion using AI-driven automation and robotics. Garment manufacturers can optimize production schedules, reduce waste, and increase efficiency because AI algorithms can analyse data to determine the most effective production methods, minimize energy consumption, and optimize the use of resources [73]. This not only results in reduced emissions but also enhances the overall sustainability of the manufacturing process. Regarding materials sourcing and selection, AI plays a crucial role in transforming the way materials are sourced and used in the fashion industry. This can be achieved by leveraging AI-driven analytics that can analyse the environmental impact of different materials, providing insights into more sustainable alternatives. This enables fashion brands to select materials that are environmentally friendly, biodegradable, and require fewer resources to produce [74]. With AI-driven technologies, fashion brands can implement more efficient and effective recycling and reuse programmes [75]. AI algorithms can identify opportunities for

recycling and reusing materials, enabling brands to close the loop and reduce waste [76]. Additionally, AI can facilitate the tracking and tracing of materials throughout their lifecycle, ensuring transparency and accountability in the circular economy [77]. Furthermore, AI has enabled personalized shopping experiences, virtual fitting rooms, and improved supply chain optimization, all to reduce waste and improve sustainability. AI-powered fashion recommendations and virtual try-on technologies help consumers make more informed purchasing decisions, reducing the likelihood of returns and ultimately reducing waste [78,79]. AI algorithms can optimize inventory management and demand forecasting, enabling brands to produce the right number of garments, minimizing overstock, and reducing the environmental impact of excess inventory [80]. This, in conjunction with the Internet of Things (IoT), blockchain technology, and big data analysis, offers an extensive array of capabilities, including device-to-device communications, and cyber-physical systems that significantly influence the fourth industrial revolution [81]. More creative and efficient approaches to clothing design have been made possible by the widespread use of intelligent design assistants, fashion style analysis, creative generating, and size customization [82]. Additionally, fashion labels and clothing manufacturers may make better use of their resources thanks to AI algorithms, which lower costs and increase productivity, effectiveness, and efficiency [83]. AI-enabled fashion blockchain made up of interconnected blocks of information, guarantees traceability systems where every activity and transaction is visible, trackable, and retrievable resulting in transparency, and guarantees a decrease in the adverse effects of fashion products on the environment [75]. Therefore, the industry's path toward balancing growth and sustainability will be determined by the availability of technology, interoperability standards, and transparent reporting frameworks.

4.3. Materials and process innovation

Sustainable fashion is greatly influenced by polymers and composites because they provide creative ways to make apparel and accessories that are both socially and environmentally conscious. Fashion labels are searching for substitutes for the materials that are already in use. As a result, materials innovations have for the past few years focused on developing environmentally friendly solutions by re-engineering traditional materials into forms that support the carbon transition. Following these developments, high-tech materials that are aesthetically pleasing with less environmental effects have been engineered [84,85].

4.3.1. Biodegradable and renewable polymers

In the area of fibre engineering, newer, safer, and sustainable fibres are presently been given priority against the conventional petroleum-based fibres on the market [86]. Research over the last few decades has found natural polysaccharide-based materials for fibres [87,88] as listed in Table 2. Most natural polysaccharides, when sustainably sourced, offer several advantages because they are biodegradable and environmentally friendly. Multiple polyester products are engineered to be biodegradable, biocompatible, and renewable. For instance, polylactic acid is produced from the bacterial fermentation of corn, sugarcane, potatoes, and other biomass [89,90].

Its sustainable properties include renewable origin, recyclability, biodegradability, biocompatibility, and bio-absorbability, making it ideal for various commercial applications. Natureworks LLC and Total-Corbion are the leading manufacturers of PLA under the brands Ingeo™ and Lumiy®, respectively [92]. PLA's properties make it a sustainable substitute for traditional plastics, with applications in industries such as medical, food packaging, textiles, and even more [93]. Compared to traditional poly(ethylene terephthalate) (PET) fibres, PLA fibres are not only biodegradable but can also be developed to have high functionality and intrinsic qualities including bacteriostatic, flame-retardant, and weather-resistant capabilities [94,95]. Another type of biodegradable polyester, poly(butylene adipate-co-terephthalate) (PBAT), was commercialized by a German chemical company, BASF, under the trade name of Ecoflex® [89]. The BASF also introduced a blend of 55 % PBAT and 45 % PLA with the trade name of Ecovio® and claimed its accelerated biodegradability than Ecoflex® under certain conditions. Having a wide range of shrinkage, tenacity elongation, modulus, and abrasion properties, PBAT is widely used in carrier bags, compostable can liners, mulch film, and food wrapping. Recent developments have also leveraged biotechnology to produce low-impact textiles that are renewable and made from algae biomass, bacteria, fungi, and agricultural wastes [96,97]. A typical example is polyhydroxyalkanoates (PHAs). PHAs are produced by a variety of microorganisms, including bacteria, that can accumulate these biopolyesters as intracellular granules. Different types of PHAs can be produced by different microorganisms under varying conditions. PHAs offer a highly promising solution to this significant ecological issue posed by synthetic polyesters because they possess properties similar to synthetic plastics, making them a viable alternative as a biodegradable and biocompatible bioplastic [98].

Bacteria cellulose (BC) has become an important textile material in the fashion industry [99] due to its many advantages. In a recent study by Phan et al. [100], leather-like BC materials were successfully synthesized in the non-woven textile fabric in a simple 3-in-1 textile finishing approach using a padding approach, which confers rich colour, softness, and unique surface patterns on the fabric. This finishing technique is waterless with high finishing efficacy. This smart manufacturing process uses no chemicals, is less cumbersome, and is environmentally friendly. Similar to this, it has been discovered that fungal leather substitutes have important mechanical and physical qualities because of the hyphal network that is interlaced throughout the fungal mycelium. Additionally, their bioactive metabolites have been linked to antibacterial activity [101]. The past few years have seen significant progress in the production of fungal (microbial-based) leathers as discussed extensively by Ayodeji et al., [101]. Table 3 shows some companies that have invested are currently producing fungal leather as an alternative to animal leather. By 2030, the size of the worldwide market for mushroom leather is anticipated to reach USD 1.9 billion. Grand Research Store projects the market to expand at a compound annual growth rate (CAGR) of 12.2 % between 2023 and 2030 [102].

To lessen the environmental impact of livestock farming for leather production, mushroom-based leather substitutes are emerging as environmentally friendly and sustainable alternatives to various animal and synthetic leather products [103–105]. Several companies, including MycoWork, Bolt Threads, Desserto, Mycotech Lab, and Mycel have recently recognized the commercial potential of mushroom leather. These companies have encouraged collaborations with luxury brands like Hermes and Mercedes-Benz to produce raw leather, luxury goods, and car interior textiles to lessen the environmental impact of animal leather production [105]. Other renowned fashion brands, such as Adidas and Lululemon, also started launching mushroom-based leather product lines. The term "Fungi Fashion" has become a trend lately not only because of the source of the raw material but also the aesthetics that such fashionable products exude. Furthermore, sustainable building materials can be produced using leather technology based on mushrooms. Also, fish skin has resurfaced as an alternative material to replace industrial leather made using toxic chemicals in the production of parkas, boots, mittens, and hats [106]. The fish leather is not derived

Table 2
Some typical polysaccharides from natural sources [91].

Origin	Polysaccharide type
Plants	Starch, cellulose, glucomannan, pectin, hemicellulose, gums, mucilage
Algae	Algar, galactans, alginate, carrageenans
Animal	Chitin, chitosan, hyaluronic acid, glycosaminoglygen, cellulose
Bacteria	Dextran, levan, polygalactosamine, gellan, xanthan, cellulose
Fungal	Elsinam, chitin, chitosan, pullulan, yeast glucans

Table 3
Companies involved in fungal leather substitute production. Adapted from [101].

Company	Country of origin	Trade name/Brand name	Range of Products	Value (USD) *	Website
Bolt Threads	USA	Mylo	Shoes, bags, jackets	472.1	https://boltthreads.com/technology/mylo/
Ecovative	USA	Mycomposites, AirMycelium	Shoes, bags, jackets, foams	91	https://www.ecovative.com/pages/leather
Grado Zero Espace	Italy	Muskin	Jackets, Bags shoes	5	https://espace-s-lb.com/collections/leather-jackets
Mugu	Italy	Ephea	Bags, shoes, jackets,	5.7	https://mogu.bio/
MycoWorks	USA	Reishi	Bags	187	https://www.mycoworks.com/fine-mycelium-an/
MycoTech	Indonesia	Mylea	Shoes, Bags, Jackets, watch straps	1.4	https://mycl.bio/

* Value in millions of USD.

from any endangered species; rather, it is produced from salmon fish raised organically, usually as a byproduct of the smoked salmon industry. Currently, there are over 16 global companies producing fish leathers [107] whose market target is mainly luxury fashion. The fish leather market was valued at USD 103.0 million in 2023 and is expected to reach USD 133.2 billion by 2032, with a projected CAGR of 2.9 % during the forecast period (2024–2032) as shown in Fig. 7 [108]. These innovations in leather products not only reduce reliance on traditional cattle farming, which is notorious for its high carbon emissions and land use but also create new economic opportunities for communities engaged in sustainable practices. The carbon footprint associated with conventional leather production is substantial. Traditional tanning processes often involve toxic chemicals and extensive water usage, contributing to pollution and environmental degradation. However, sustainable leather initiatives prioritize eco-friendly tanning methods and utilize byproducts from the fishing industry, thus promoting a circular economy. Similar sustainable efforts are ongoing across the entire textile value chain to reduce the carbon footprint of fashion products.

Recently, the spinning of fibres from unconventional materials such as carrageenan, residual soybeans, peanut protein, etc., into value-added woven and nonwoven textile materials for various fashion products has gained significant momentum as an environmentally friendly alternative to conventional textile materials [109].

While some of these innovations may be perceived as potential threats to food security, their development has not yet reached a level of significance that could substantially impact this issue. Nevertheless, the benefits they offer in terms of reducing carbon footprints outweigh these concerns. In light of such apprehensions, recent advancements have increasingly focused on unconventional materials as alternatives to those derived from petrochemicals. In this regard, Svensson [110] wet spun zygomycetes fungus into sustainable monofilament yarns with potential commercial application in the fashion industry. Aumnate et al. [111] synthesized polylactic acid (PLA)/kenaf biocomposite filaments fibre via melt-extrusion process in the formation of sustainable textile fibres for applications in functional apparel. More extensive and focused research and reviews have been undertaken on sustainable textile materials for the fashion industry [112–114], hence the discussion here is only brief.

4.3.2. *Colouration and finishing*

Sustainable colouration and finishing are integral to the fashion industry. This aspect of manufacturing is notorious for contaminating water bodies, land, and air pollution. Sustainable fashion colouration focuses on implementing environmentally friendly and socially responsible approaches in these processes. Sustainable fashion strives to minimize the environmental impact of colouration and finishing while maintaining the aesthetic and functional qualities of textiles and clothing. It does this by promoting eco-friendly finishing techniques, using non-toxic chemicals, adopting eco-friendly dyeing and printing methods, and the enactment of responsible waste management by dye houses. Sustainable colouration has received significant research attention over the last decade and some very comprehensive and important reviews have been published [115–118], hence, only a few recent studies will be highlighted. Thanks to developments in biotechnology, microbial dyes derived from microalgae, yeast, moulds, bacteria, and cyanobacteria have been developed. These colours can be grown in bioreactors or enhanced through biotechnological procedures [119]. These dyes can be produced through fermentation processes using

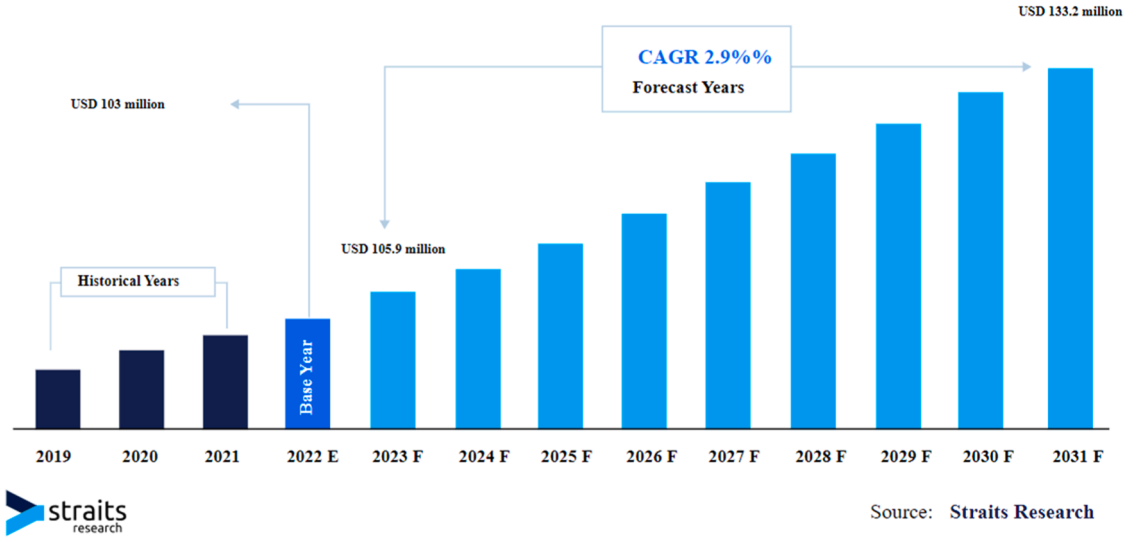

Fig. 7. Estimated global fish leather market [108]. Reprinted with permission from Straits Research.

renewable feedstocks. Microbial dyes offer a sustainable and potentially more eco-friendly alternative to traditional synthetic dyes, as they have lower environmental impacts and can be produced with minimal chemical inputs. In recent years, microbial dyeing has emerged as a sustainable alternative, utilizing the natural capabilities of microorganisms to produce vibrant and eco-friendly dyes for textiles. This innovative approach taps into the natural metabolic processes of these microorganisms, which can produce a variety of pigments. For instance, certain strains of bacteria can generate colours ranging from deep reds to bright yellows, while fungi can produce rich, earthy tones. These microbial dyes are not only biodegradable but also less toxic, making them a safer option for both the environment and human health. In a recent colouration innovation, Nakpan and Sirinkraporn [120] designed a melanin-like brown colour thin, light, and smooth cellulose sheet with lines resembling human skin from soil harbouring favourable Streptomyces bacterium. They then transformed the material into an amplituhedron dress to Thai people's skin colour, with the hue determined by employing the Fitzpatrick skin prototype (as illustrated in Fig. 8a-d). This technique provides a sustainable means of providing functional coloured textile material with no environmental consequence. This thus exemplified a green fashion trend which potentially creates a new design standard that highlights aesthetics. Utilizing bio-based ingredients and the Do-It-Yourself (DIY) method, Bell, McQuaid, and Alistar [121] designed a fully sustainable cloth (see Fig. 8e-g) by heating, chopping, blending, and setting alganyl (a product made of water, glycerine, and agar) in a microwave. The study's conclusions suggested that it might lead to a time in the future when clothes serve as a free-standing means of self-expression with little environmental impact. One of the key advantage of microbial dyeing is its potential to significantly reduce the carbon footprint of the textile industry. The cultivation of microorganisms typically requires fewer resources than traditional dyeing methods, such as water and land. Additionally, microbial dyeing can often be conducted in controlled environments, reducing the need for harmful chemicals and minimizing waste. This shift towards microbial solutions not only addresses environmental concerns but also promotes a circular economy, where waste materials can be repurposed as substrates for microbial growth. Despite the obvious benefits of microbial dyeing, the technology for full-scale industrial integration is still in its infancy, and scaling up production to meet the demands of the fast fashion industry can be difficult. Moreover, the colourfastness and consistency of microbial dyes may vary, which can hinder their acceptance in mainstream textile applications. That notwithstanding, recent research and advancements in biotechnology are addressing these issues, paving the way for more reliable and effective microbial dyeing processes.

Also, waterless colouration innovations such as air-dyeing, foam dyeing, supercritical, and subcritical colouration technologies have significant reductions in water usage, energy consumption, and chemical waste associated with traditional dyeing processes [122–125]. These developments improve the overall sustainability of the textile business, reduce pollution, and protect water resources. Additionally, waterless colouration technologies offer increased flexibility, efficiency, and customization options, enabling fashion brands to respond to changing market demands and reduce production lead times while maintaining their sustainability targets [125]. For most synthetic fibres, colouration techniques based on supercritical technologies that require no water or very little water have been marketed [126,127]. Gupta and Shukla [128] employed a cutting-edge technique for dying textile materials that uses less energy, water, and waste by applying a dry-dye process to recycled polyester made from PET bottles. Other waterless colouration

Fig. 8. Examples of sustainable fashion clothing: (a) Amplituhedron dress; (b) Amplituhedron dress no 2; (c) Amplituhedron dress no 3; (d) Amplituhedron dress no 4. 120]; An alganyl biotextile DIY clothing made into (e) a dress, (f) a shirt, (g) a skirt [121].

techniques, such as air dyeing and foam dyeing, minimize or eliminate the use of water in the dyeing process. These methods use alternative mediums, such as compressed carbon dioxide or foam, to transfer colour to the fabric. Waterless colouration reduces water consumption, eliminates waste and reduces carbon footprint. Natural and low-impact synthetic dyes have been developed to minimize their environmental footprint [129]. These dyes are typically classified as eco-friendly because they require less water, energy, and chemicals during the dyeing process. They are designed to have high absorption rates, resulting in reduced wastewater discharge and improved colour fastness [130]. Also, digital printing technology allows for precise colour application directly onto textiles, eliminating the need for excessive dyeing and rinsing processes [131]. It uses a great deal less water, energy, and chemical waste than conventional printing techniques. Digital printing technology allows for precise colour application directly onto textiles, and direct-to-garment printing places photo-realistic imagery on finished products such as t-shirts, hoodies, and bags. Piezoelectric nozzles precisely control microscopic droplets of specially formulated ink eliminating the need for excessive dipping, rinsing, and drying processes [132]. It significantly reduces water consumption, energy usage, and chemical waste compared to traditional printing methods. Digital printing also enables design customization and on-demand production, and therefore, contributes to waste reduction and prevents overproduction [132].

In the area of environmental remediation, most dyes can be degraded photochemically or biologically using microbes. There is a lot of research being done on the application of bioremediation-based technologies for treating dye house effluent, and their mechanism is well understood [133]. Extensive research work and reviews have been written on this; hence further reference can be made from these articles [134–138]. An important progress in environmental remediation is the use of Microbial Fuel Cells (MFCs). MFCs have emerged as a promising technology for sustainable dye degradation utilizing electroactive bacteria through the power of microbial metabolism. MFCs offer the unique advantage of simultaneously treating wastewater and generating electrical energy. In the MFC process, as the bacteria break down the dyes, they release electrons, which can be captured and utilized through an electrode system to generate electrical energy as shown in Fig. 9a. This characteristic makes MFCs an attractive option for sustainable dye degradation, as they not only treat wastewater but also produce usable electrical power. A comprehensive description of the mechanism, variations, and large-scale applications have been described elsewhere in a comprehensive review by Sonawane et al. [139].

Despite the significant progress in bioremediation, degradation of big organic dyes is mostly achieved by photodegradation [140,141]. The degradation of big dye molecules involves a series of advanced oxidation reactions. Because advanced oxidation reactions are non-selective, they can eliminate practically all organic pollutants [141]. The advanced oxidation of dyes can be achieved through various methods, including chemical reactions with a catalyst and reagent, photochemical reactions utilizing UV light or solar energy, electrochemical reactions powered by an electric source, and sonochemical reactions employing ultrasonic technology, making it significantly faster than conventional techniques due to its highly reactive nature. The simplest of these oxidation techniques is photodecomposition, which uses ultraviolet light (UV light) to break down H_2O_2 and O_3, creating an OH radical that breaks down contaminants like dyes [142]. The light energy that is absorbed during this process can result in direct photolysis, sensitized photolysis, and indirect photolysis, among other transformation processes. Advanced oxidation process details have been covered in depth elsewhere [143, 144]. Dopant and heterojunction-based semiconductor metal sulfide nanostructures (MSNSs) nanostructures that function as photocatalysts

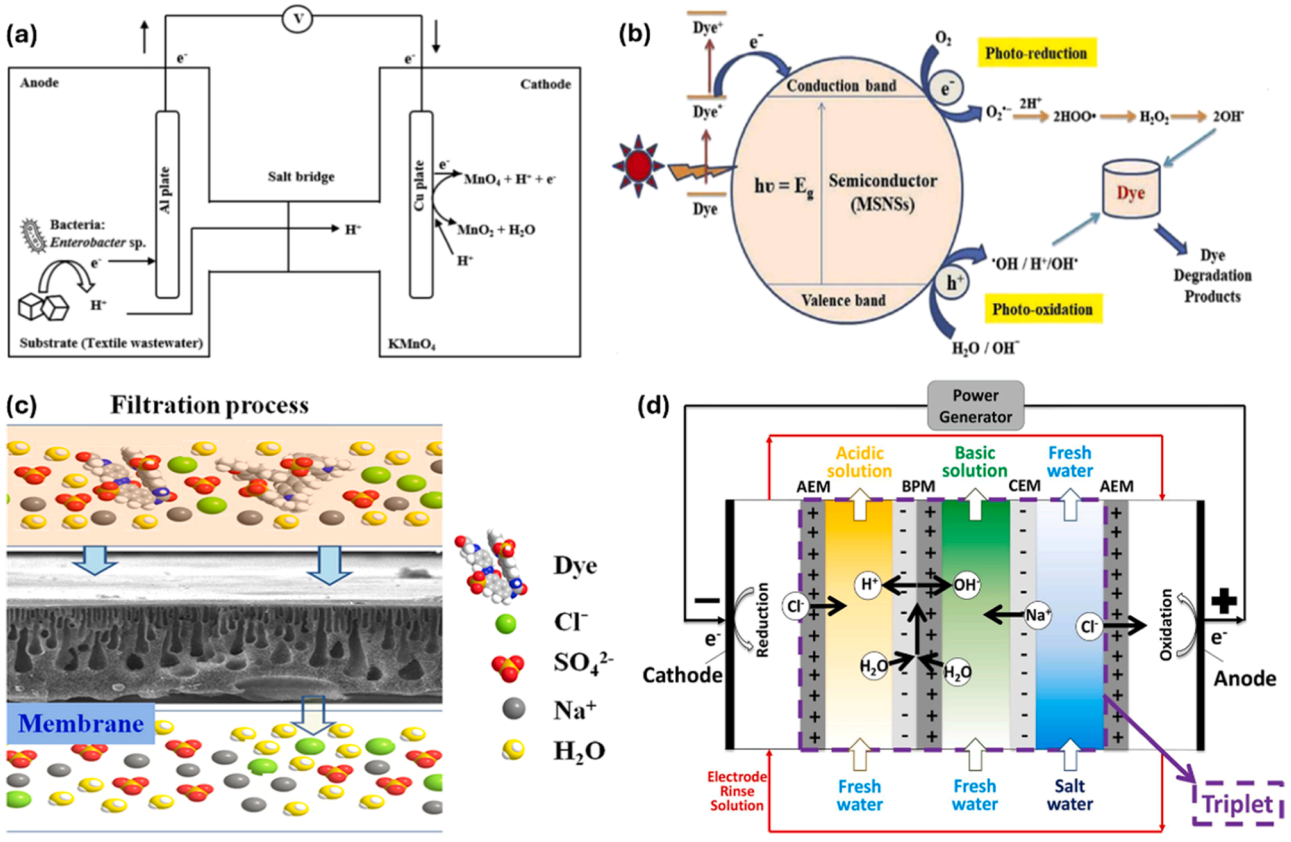

Fig. 9. Schematic representation of the MFC working mechanism [139]. (b) Diagrammatic representation of the process of photocatalytic dye degradation using semiconductor metal sulfide nanostructures exposed to light [145], (Reprinted with permission from Elsevier under CC license). (c) An illustration of the hybrid tight ultrafiltration (TUF) filtration process, (d) A schematic illustration of bipolar-membrane electrodialysis [148]. (An open-access article under CC license by Elsevier).

have been thoroughly studied for the environmentally benign and sustainable degradation of large organic dyes through photocatalysis to address environmental pollution caused by textile manufacturing companies [145]. Fig. 9b shows the general method of organic dye degradation by photocatalysis utilizing several types of MSNSs. The impacts of different dopants, heterojunctions, band gap, size, light intensity, surface area, response time, and degradation efficiency have all been thoroughly explored recently due to their high efficiency and environmentally benign nature [145,146].

Similar to this, extremely saline textile wastewater can be recovered with hybrid tight ultrafiltration (TUF) and bipolar-membrane electrodialysis (BMED) methods as illustrated in Fig. 9 (c-d). TUF is a pressure-driven membrane filtration process that removes contaminants based on size exclusion, while BMED is an electrochemical separation technique that selectively transports ions and generates acids and bases. These processes can recover dye effluent, acid/base conversion, and pure water regeneration [147].

4.3.3. *Production process automation*

To overcome the environmental and social issues facing the fashion industry, innovations in sustainable fashion production are becoming more and more crucial. Various technologies and practices have emerged to promote sustainability throughout the fashion supply chain. Automated manufacturing processes and robotics have played a critical role in the march toward net-zero emissions in the fashion industry [149,150]. Computer-aided-manufacturing enables precision cutting and reduces fabric waste by optimizing pattern markers, minimizing errors, and maximizing material utilization [151]. Additionally, automation has helped fashion and textile companies streamline production lines, reduce energy consumption, and improve overall efficiency in textile and apparel manufacturing [152,153]. For instance, the use of 3D virtual prototypes has reduced significant carbon generation processes compared to the traditional modus operandi [154] by saving lots of materials and international shipping efforts. Laser cutters equipped with advanced vision technology detect the surface properties of fabrics and eliminate excessive use of inks, chemicals, and solvents, which makes the entire process environmentally benign [151]. More importantly, laser technology eliminates inks, chemicals, and solvents, which makes the entire process environmentally benign. Such automation processes run accurately, produce less waste, improve production quality, swift processing, and use less energy [155].

Also, novel fabric production processes that eliminate weaving and cutting steps in garment production have been engineered by an Indian designer Siddhartha Upadhyaya designed direct panel on loom (DPOL) can be made to speed up the textile and garment production process [156]. The DPOL process can be immediately woven into ready-to-sew pieces on a loom following computerized processing, considering both the texture and patterns. Other important developing technologies include negative tailoring, 3D printing, seamless knitting, and biological fashion [157]. These technologies minimize waste by focusing on essential design elements, conserving resources and reducing environmental impact while allowing for precise, on-demand garment production, significantly cutting material waste and transportation emissions. Similarly, emissions from the use of hazardous chemicals as well as the creation of safe working conditions are paramount to the sustainable fashion discourse. Therefore, finding alternate manufacturing options for potentially dangerous and injurious textile and garment manufacturing processes remained an important area of research by the fashion industry [89]. Recently, robotics and automation have been achieved in garment cutting and sewing. This automation reduces human error and prevents production mistakes, which raises productivity and enhances the quality of fashion items. Specifically, significant progress has been made in mechanized fabric handling, computer numerical control (CNC) cutting, automatic stitching machines, and fully automated robot manufacturing [115,151]. With the current advancement in AI, clothing production lines autonomously self-organize and self-optimize using machine learning algorithms and real-time data thanks to smart automation interoperability and connection technologies [55]. These protocols aid in guaranteeing that workpieces flow automatically through a process or between processes.

In recent years, the textile industry has abandoned some of its chemically dangerous manufacturing processes in favour of safe nanotechnology techniques, enzyme technology, and/or bioactive ingredients in traditional wet chemical processes. This has produced high-performing, eco-friendly, and multipurpose products for a variety of applications while taking social, economic, and ecological concerns into account [158–160]. It is envisaged that the application of ionic liquid in various production and chemical processes will be practicable soon [161]. For instance, current advancements in the denim industry, like "Ego" allow clothes to be treated with ozone in both water and air to provide the appearance of true bleach without the use of hazardous chemicals. Similarly, new inventions like the "NoStone" abrasive drum produce stone-washed effects without requiring pumice. Likewise, the labour-intensive manual abrasion processes in denim production have been replaced with laser and photobleaching processes, allowing designers greater creative freedom.

Because of the lengthy process flow chain and extensive machinery utilization in the textile sector, energy is one of the primary cost factors [162]. It has been estimated that the textile sector uses approximately 70 % of electricity and >50 % of thermal energy in its numerous processes [162,163]. To reduce this, a patented technology called "UP" circulates a steady, uninterrupted flow of water inside the processing apparatus for injection, collection, and recirculation in textile wet processing and finishing. These technologies reduce the thermal energy needed for sizing, dyeing, and drying [164]. In recent years, pollution has decreased and energy efficiency has increased due to the introduction of alternative production processes and technical advancements in some operating operations [165]. The shift represents a new direction for innovation and economic growth without compromising environmental sustainability thereby helping reduce the carbon footprint. Concerns over climate change, greenhouse gas emissions, and the loss of natural resources are the main drivers of this trend [166]. Solar energy systems have been adopted to reduce their dependence on fossil fuels, thereby reducing carbon emissions [167]. In recent times, the investment in hydropower and wind power has helped lower dependence on fossil fuels [168,169]. With the right investment in efficient energy systems and the right technology, the costs will reduce and the outputs from energy resources will increase.

4.4. *Consumer and social innovation drive*

Consumer awareness of sustainable fashion has risen in recent years driven by the “UN Sustainable Development Goals (SDGs)” Agenda 2030, COP28, and the increasing concerns from various governments and environmental advocacy groups [170,171]. Reducing the environmental impact of clothing production, supporting moral labour standards, and fostering responsible consumption are the primary underlying goals of sustainable fashion [172]. Although there has been a significant increase in consumer awareness of sustainable fashion over the past decade, some recent studies point to generational differences in the level of awareness of fashion sustainability. According to a study by Statista Consumer Insights conducted in October 2024, awareness of the term "sustainable fashion" was most pronounced among younger adults in Japan. Notably, the highest recognition was found among teenagers aged 15 to 19, with 43.4 % indicating familiarity with the concept of sustainable fashion [173]. In a similar study [174], between January 2020 and February 2023, the average number of searches for sustainable fashion brands per 1000 visits revealed that the American outdoor brand Patagonia led globally, with approximately three million monthly searches. Reformation ranked second with an average of 896 monthly searches, followed by Everlane (516), Allbirds (386), Rothys (259), Cotopaxi (177), Girlfriend Collective (138), Eileen Fisher (138), and

Nudie Jeans (124). Organic Basics had the lowest average, with 73.4 monthly searches [174]. The frequency with which the term "sustainable fashion" is searched serves as an indirect indicator of consumers' awareness and interest in exploring products from sustainable fashion brands. This heightened awareness reflects a growing desire for sustainable consumption, which necessitates that consumers make fewer purchases, extend the lifespan of products, and reduce waste. By connecting brand awareness to these behaviours, it becomes evident that informed consumers are more likely to engage in practices that support sustainability in the fashion industry. In this context, Product Service Systems (PSS) can offer a valuable framework by combining techniques that encourage greater consumer involvement, such as participatory design and customization, with commercial models like renting, upcycling, and redesigning. Together, these elements create a more engaging and sustainable approach to fashion consumption [175]. This will help maintain environmental friendliness, economic stability, and innovations for sustainable consumption considering human instincts and desires. Instinctively, even among the more morally conscious consumers, moving away from fast fashion is difficult [176]. Even the most morally upright people consume "grey" goods and are vulnerable to programmed obsolescence across the fashion cycles [177]. The ability of consumers to demand and obtain new goods and services that satisfy not just their ingrained tastes for costs, fashions, and quality, but also social and environmental standards, has risen [178]. Consumers who care about the environment place a high value on social values in the community and the usefulness of recycled apparel [179]. The decision to purchase environmentally and socially conscious items is often influenced by consumer preferences for other product features like price, quality, style, and design in addition to environmental and social issues. According to Statista Consumer Insights [180], approximately 81 % of Indians purchase eco-friendly and sustainable fashion, compared to 69 % 49 % 41 %, and 39 % of China, the USA, Germany, and the UK, respectively (see Fig. 10).

The purchasing decision of fashion products by consumers is not only influenced by economic factors but also by complex ethical and cognitive reasoning [181]. Other research studies have suggested that age and gender are important predictors of consumers' intentions to purchase sustainable clothing or otherwise [182]. Therefore, Rahman et al. [183] examined the consumer behaviour of Polish people towards the purchase of sustainable and non-sustainable products using several matrices against gender and age.

It was found that a large percentage of consumers would not buy sustainable or "green" products if they did not meet their needs and goals

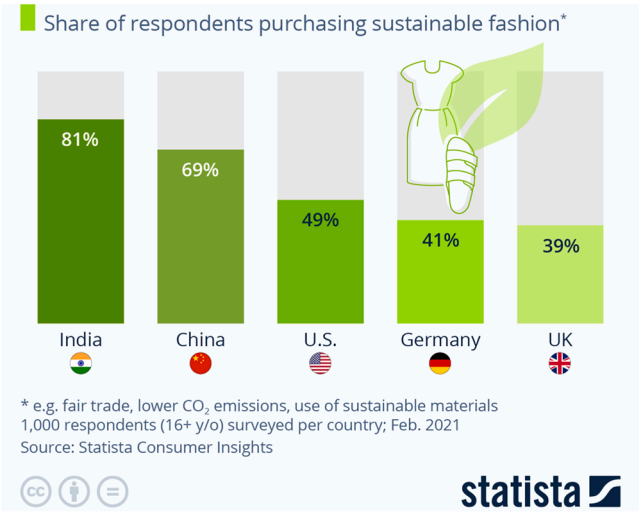

Fig. 10. Share of consumer purchasing of sustainable fashion [180]. An open access figure From Statista under CC BY license.

in terms of appearance, functionality, and affordability. With regards to gender, it was realised that women were more dependent on clothing fit and style with less regard to sustainability than men. This indicates that sustainable fashion should not only advocate environmental, social, and ethical benefits but must also satisfy the aesthetic, symbolic, functional, and financial needs of consumers. In a study by Koszewska [178], the sustainable consumption pattern of Pole consumers was investigated and the results showed that the buying patterns are influenced mostly by ecological and social considerations. In a similar study by Gadhavi et al. [184], it was revealed that young Indian consumers were quite reflexive and cognizant of their social groupings, social references, and social image in their choice of fashion products. Drawing from several studies on the fashion buying behaviours of young adults, it is reasonable to infer that peer acceptance, price, accessibility, and social trends determine the majority of young consumers' fashion consumption [185]. However, depending on the geographical location, social norms and other factors, fashion sustainability could be oversimplified to mean clothing repair, less frequent laundry, and other circular economy practices as sustainable clothing consumption [186]. Although there are disparities in the comprehension of the notion of sustainable fashion, environmentally and socially conscious products have generally received a more favourable reception from consumers. For instance, 84.3 % of South Korean consumers favour sustainable and ethical fashion products indicating their belief in sustainable fashion-related endeavours [187].

4.5. *Policies and regulatory frameworks*

The structural change needed for an ethical and sustainable industry has not been historically attained by businesses' voluntary activities. This historical antecedent must therefore guide how governments approach the sustainable fashion quagmire for a greener future. For the sector to move more quickly towards ethical practices and a net-zero future, enforceable regulatory frameworks are required [188]. Since the 1987 release of Brudtland's study, originally drafted in 1992 and revised in 2002, sustainable development (SD) and sustainability have progressively made their way into public policy and business strategy [189]. Agenda 21 established a framework for action on sustainability challenges at the international, national, and local levels [190]. This has prompted the creation of sustainability measures along the three axes of fashion (namely materials innovation, supply chain transparency / fair trade, and sustainable consumption habits), such as the indicators put forth by the UN Commission for Sustainable Development, and the Transcontinental Accords like the Kyoto Protocol on climate change [190]. Two initiatives that highlight how the practices used by the fashion industry impact the environment are Textiles 2030 and the UN Sustainable Development Goals [191]. Governments and economic blocs have for the past few decades introduced various regulations to reduce carbon footprint fashion. For instance, the UK government has since the Textiles 2030 initiative enacted policies that aim at curbing the worst excesses of the fashion sector since 2007 [192]. It introduced the Sustainable Clothes Road Map (SCRM) in 2007, compiled data on the effects of clothes on the environment across time, and created a sustainable vision outlining the immediate, intermediate, and long-term actions to guide the sector [192]. In most of these initiatives, bottom-up strategies are usually employed in policy initiatives due to the rejection and relative ineffectiveness of top-down measures as well as the growing recognition that diverse techniques are necessary to include consumers in lessening the impact of fashion [192].

The implementation of certification standards aids in the definition and control of sustainability claims. Concerning textile materials and products, the Oeko-Tex Standard 100 is the most representative ecological barrier, ensuring that textile products do not endanger human health or the environment [193]. Equally, regulatory frameworks such as the International Organization for Standardization (ISO) published a standard framework that outlines four stages of a life cycle assessment

(LCA) [194]. Though ISO 14,044 outlines specifications and criteria for LCA, ISO 14,040 essentially covers the ideas and framework of LCA [195]. While international cooperation on fashion policy initiatives is still crucial, it is important to acknowledge that standardization levels the playing field and ensures that leaders in sustainability don't face unfair disadvantages. It is, therefore, recommended that governments must balance prescriptive regulations against flexibility for continued innovation [30,196]. Equally, policy combinations including both voluntary and mandatory measures tailored to make an impact can act as catalysts, not constraints, to spur the industry's transition to a net-zero and socially just future.

4.5.1. Government policies and initiatives

Governments are being compelled by the growing urgency of addressing climate change worldwide to adopt stronger environmental legislation to reduce greenhouse gas emissions. In the wake of the June 2015 Rana Plaza catastrophe, the G7 Leaders' Declaration evaluated international efforts to create industry-wide due diligence standards for the ready-to-wear and apparel sector [197]. Global agreements like the United Nations Paris Climate Agreement further put pressure on the fashion sector to address its environmental impact. As a result, 195 nations have pledged to limit global temperature rise to <2 °C [198, 199]. The implementation of collaborative governance efforts can provide the necessary systemic changes to address sustainability concerns in a variety of fields. A range of formal and informal, legally enforceable, and voluntary agreements involving market players, civil society organizations, and states are included in governance efforts. Additionally, single-actor entry points like laws that indirectly affect other actors are included [200]. For instance, tax policies may help lessen the detrimental effects of consumption, both generally and specifically about fashion on the environment [201]. Currently, export markets have standardized sustainability labelling verifications to protect integrity. Examples of these are the Energy Star (Emidast) sign from the Environmental Protection Agency of the United States, the EU's sign, which is a flower with twelve stars, TCO's sign in Sweden, "Svanen (Standardiseringskommisionen i Sverige)", "Umweltzeichen" in Germany, and Environmental Choice in Australia [202]. Notably, global pledges such as the "UN Fashion Industry Charter for Climate Action", a movement that advocates science-based emission reduction goals [203]. Such multi-national and country-specific regulations significantly influence industrial development towards sustainable, circular, and fair models that counterbalance the historical disadvantages of fashion through norms, incentives, and systemic reconfiguration [22]. Regulation in the fashion industry can foster greater stability, facilitate market consolidation, enhance average profitability, and ensure strict compliance with established rules. For instance, a cursory analysis of a few regulations of the fashion industry in some Asian countries is presented in Table 4.

4.5.2. Industry standards and certifications

Standards and certifications are essential instruments for driving ethical practices across intricate global supply chains as the fashion industry grapples with environmental and social issues [204]. As noted by Fontana et al. [205], compliance with these protocols signals to consumers that brands are aligning processes with defined ethical and sustainable benchmarks beyond legal minimums. Unfortunately, obtaining environmental performance certification via eco-labelling is entirely voluntary [206]. However, these labels mark an important milestone for the fashion industry in the attainment of sustainable fashion because consumers have become increasingly aware of their fashion choices. The largest global registry of ecolabels, the "Ecolabel Index," keeps track of over 456 ecolabels across 199 countries, spanning 25 industry sectors [43]. The implementation of green labelling as a standard is a significant step toward addressing the issue of environmental degradation for sustainable development [206]. Approximately one hundred ecolabels are applied in the textile sector at the national and international levels, covering various phases of the production life

Table 4
Examples of some government's initiatives in Asia.

No.	Country/ region	Name of initiative	Purpose
1	China	Green Fence Policy (GFP)	• China's GFP restricts the import of low-quality and contaminated recyclable materials, including textiles, which encourages higher quality and more sustainable recycling practices.
		China Environmental Labelling Program (CELP)	• CELP is a voluntary eco-labelling initiative that certifies textiles meet environmental standards.
2	Hong Kong	Hong Kong Green Label (HKGL)	• The HKGL eco-label certifies a wide range of products, including textiles, based on their environmental performance. • It assesses variables like emission control, waste minimization, and resource conservation.
3	Taiwan	Green Mark Program (GMP)	• GMP is an eco-labelling scheme that certifies environmentally friendly products, including textiles that meet specific criteria. • It evaluates products based on environmental criteria such as energy efficiency, resource conservation, and reduced environmental impact.
4	Japan	Japan Organic Cotton Association (JOCA) Certification	• JOCA is a certification system for organic cotton products. It ensures that cotton products meet specific organic standards, including the cultivation and processing of cotton fibres.
		Japan Textile Products Quality and Technology Center (QTEC):	• QTEC provides certifications for textile products that comply with environmental and safety standards.
5	Thailand	Thailand Green Label (TGL)	• The TGL is eco-labelling certified products, including textiles, based on their environmental attributes. • It assesses factors such as energy efficiency, water conservation, and reduced environmental impact.
6	South Korea	Korea Eco-Label (KEL)	• The KEL certification evaluates and certifies various products, including textiles and clothing, based on their environmental impact. • It takes into account things like protecting the environment, preventing pollution, and ensuring product safety.
7.	Malaysia	Green Mark Malaysia (GMM)	• GMM is an eco-labelling initiative that certifies products, including textiles, based on their environmental performance. • It assesses things like resource conservation, energy efficiency, and the usage of eco-friendly products.
8.	Singapore	Singapore Green Label (SGL)	• SGL is an eco-labelling initiative that certifies products, including textiles, that meet specific environmental criteria. • It evaluates elements including water conservation, energy efficiency, and the usage of sustainable materials.

cycle. The most common eco-labels used in the global textile industry are "Oeko-Tex Standard 100", "Global Organic Textile Standards (GOTS)", "Better Cotton Initiative", "Organic Exchange Standard", and "Organic Content Standard" [207]. These eco-labels assure consumers that the product has undergone rigorous environmental and social evaluations. Others include BMP Certified Cotton originating from Australia, the bluesign®, and the fair trade symbol - all certify that fashion raw materials and production processes are environmentally friendly and consistent with the general sustainability guidelines [208–210]. Some examples of the eco-labels are shown in Fig. 11 with a brief explanation of the aims. As observed by Shim et al., [211] these ecolabels facilitate consumers' decision-making process by fostering transparency and confidence. With minimum price guarantees and ecologically friendly procedures for cotton and other natural fibres, Fairtrade International Textile Standard (FITS) places a strong emphasis on improving farming circumstances [212]. Beyond the effort of the FITS, ISO standard ISO 14,040 (Life Cycle Assessment (LCA)) measures the full impact that every phase of the supply chain produces and establishes "hotspots," or potential places for decreases [194]. Based on this, the Sustainable Apparel Coalition (SAC) created the Higg Index, which rates each stage of the production process - factories, packaging, ingredients, dyeing and finishing, and branding in terms of social and environmental sustainability [213,214]. More so, many fashion business have adopted proactive benchmarking their standards thereby facilitating practice improvement through the use of performance indicators and iterative self-assessment scores [215]. Stricter certifications are being widely adopted throughout supply chains, which helps to normalize sustainability, fight back against laggards, and honour industry leaders who are transforming the industry toward ethical, net-zero fashion [216,217]. This promotes sustainability from the bottom up, utilizing commodities that are frequently entangled in destitution and excessive chemical use.

4.5.3. *Stakeholder engagement and collaborations*

The fundamental structure of the SDGs recognizes the vital significance of partnerships and stakeholder participation as indicated by the United Nations Department of Economic and Social Affairs (UNDESA) objective, "To make decisions on sustainable development, all stakeholders must actively participate" [219]. In that document, agenda 21 advocates a shift to sustainable production and consumption by encouraging the development of a framework of initiatives to support national, state, and local initiatives during the Rio Earth Summit [220]. As a result, more businesses now view sustainability as a crucial strategic concern [221]. The fundamental components of inter-organizational relationships are achieved through alliances based on shared vision, buyer-supplier ties, and cross-sector collaborations [222]. Governments, businesses, and consumers are working together to create a real systemic transformation and expedite the adoption of technologies and circular business models that will speed the transition to a circular economy [41]. Achieving this requires a collaborative effort from NGOs, technical experts, and policies that offer incentives for sustainability. Corporate Social Responsibility (CSR) is long been recognised as a crucial initiative for fashion businesses to help them balance their obligations to the economy, society, and environment while also satisfying the demands of their shareholders and stakeholders [223]. It is through such efforts that sustainable development can be meaningfully achieved. An effective CSR strategy propelled by comprehensive stakeholder engagement fosters trust, sharing, and the development of societal values [175]. The values translate into collaborative consumption, which offers an opportunity for the fashion industry to develop novel and sustainable business models that attract market competency in addition to sustainability and adequacy [224]. Such collaborative consumption models eases environmental concerns by promoting recycling and reuse of current items, which can help reduce the amount of garbage that ends up in landfills. Currently, companies such as Renewcell (Renewcell, Stoccolma, Sweden) [225], AlgiKnit (AlgaKnit, New York) [226], and Pinatext (Ananas Anam, London, England) have collaborated with other brands to optimize their end products sustainability performance [227]. Also, ACBC (a sustainability consultancy) and Pinatext have collaborated to develop a circular sneaker, similar to the Levi's® 501® [84]. An openness to collaborate across the value chain can accelerate the transition to net-zero goals while producing a fashion system that benefits

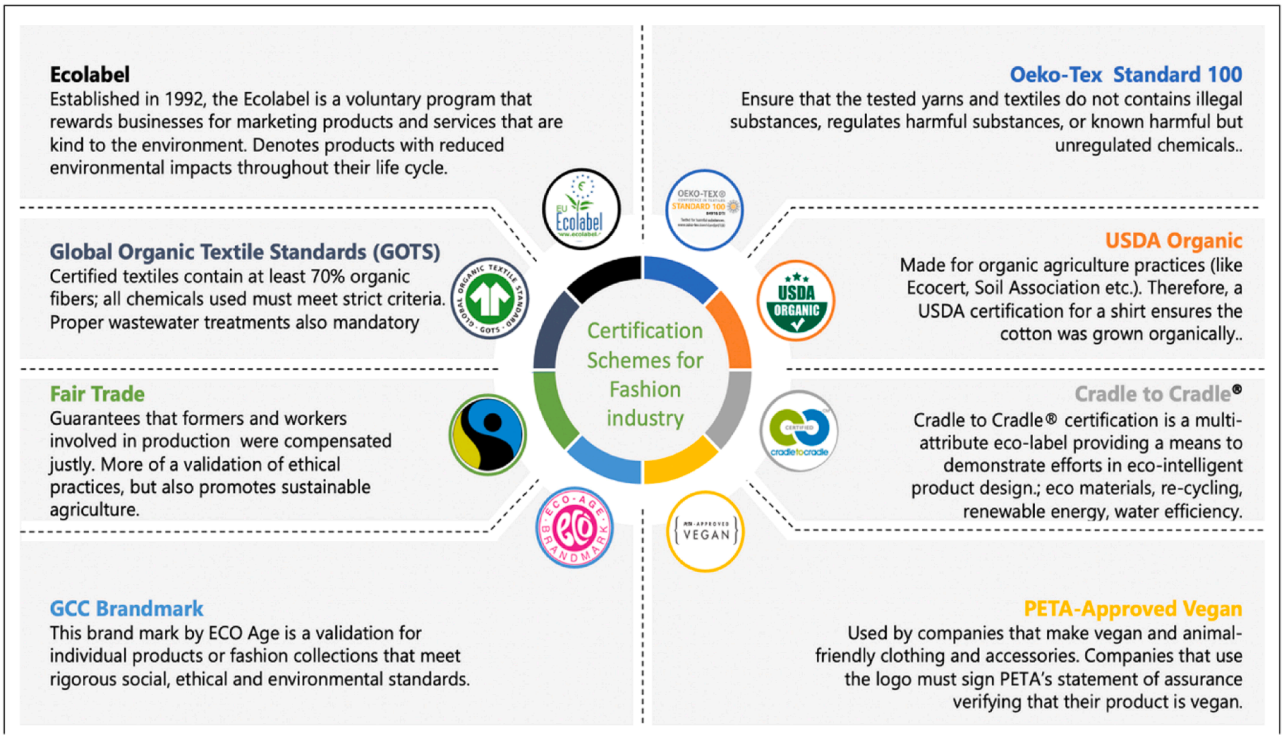

Fig. 11. Some certification labels (ecolabel) under the ecolabel index in fashion/textiles. Reprinted with permission from [218].

people and the planet. The involvement of all industry stakeholders, brands, manufacturers, multi-stakeholder organizations, non-profits, policymakers, and consumers is crucial for the holistic attainment of sustainable fashion [228]. NGOs like the Fair Wear Foundation advocate have had customers boycott fashion products (like the one against Nike in the 1990s) in response to the negative effects of fashion [229,230]. Currently, NGOs have taken a more formal role in keeping the fashion industry accountable for its deeds [198]. NGOs' perspectives on fashion businesses have evolved because they are now seen as essential collaborators in advancing societal good rather than mere pressure groups [231]. As a result, fashion companies have accepted the challenge from the NGOs for strategic and ethical reasons [219].

Government regulations and customer demands for environmental friendliness have pushed fashion businesses to strive for more sustainability while meeting important metrics like performance, comfort, and aesthetics [231,232]. The fashion ecosystem must reinvent itself to support the people and natural resources that sustain it through cooperative initiatives that strike a balance between economic needs, environmental constraints, and social development [233]. Therefore, businesses and other organizations need to fulfil their social and environmental obligations by participating in multi-stakeholder partnerships that promote sustainability goals [234,235]. In this ecosystem, legislations foster favourable conditions for systemic change by enacting laws, providing incentives, investing in infrastructure, and setting public procurement guidelines [236]. Institutions and fashion businesses respond by engaging in activities that reduce environmental impact while helping the consumer appreciate sustainability [237]. Research plays a pivotal role within the collaborative ecosystem by generating evidence on sustainability issues to inform policy and corporate strategy [219]. Such informed positions enhance stakeholder engagement on sustainability help institutions better understand the state of the market, enhance their reputation, foster long-term partnerships based on trust, and identify and reduce business-related risks and uncertainties. For instance, a commitment to the UN due diligence guidelines could help fashion brands and businesses understand and uphold human rights [200]. This will promote industry-level collective bargaining and cooperative efforts by trade unions to enhance the welfare of fashion manufacturing workers [200]. Collaborative innovation is needed to address both emerging and persistent problems because such efforts break down cultural barriers [238]. Similarly, risks, resources, and knowledge can be shared through strategic partnerships with innovators, non-governmental organizations, and recyclers. Thus, through instruments like environment, social, and governance (ESG) integration, shareholder involvement, and preferential lending rates, investors can evaluate sustainability risks and opportunities to direct capital flows toward responsible enterprises [239]. Through robust social dialogue, public-private partnerships, collective investment, and policy advocacy, stakeholders across sectors can leverage resources, and voices to transition fashion toward an ethically and ecologically regenerative system.

5. Recommendations for achieving net-zero emissions

With the fashion industry acknowledged as the second largest environmental polluter, it is important to accelerate the transition to a net-zero future to lessen the looming climate catastrophe. Following the UNDP SDGs Agenda 2030, the fashion industry must align its operations to meet these goals [9,240]. To make this a reality, the industry must balance anthropogenic emissions by sources and remove sinks of greenhouse gases in the second half of this century, consistent with the net-zero goals [241,242]. To achieve these goals, strong social and environmental principles that guarantee biodiversity preservation, strong social safeguards, and the restoration of naturally occurring ecosystems must be adhered to [243,244]. Statutes and enforceable policies are the most effective tools for monitoring and changing short-term decisions for long-term policy signals. A legal commitment will ensure that net-zero targets become transformative tools that propel action towards achieving the objectives of the Paris Agreement, rather than merely aspirational ideals that do not influence decisions [240].

A 2020 report on the Carbon Neutral Protocol (CNP) by the Climate Capital Partners (CCP) provides further recommendations for achieving a net-zero economy in a business [245] (refer to Fig. 12). This recommendation could be adopted by the fashion industry to accelerate the transition. If the current rhetoric doesn't change, the fashion industry will be responsible for 26 % of the world's carbon emissions by 2050, up from its current 10 % share [246]. It is, therefore, important that industry adopt the CCP protocol with the circular economy models and integrate them with the SDGs [9,247].

To minimize consumption and production, a mix of technological and social measures must be used to extend the lifespan of garments, minimize the impact of manufacturing, and replace worn-out equipment with AI-enabled digital twin technologies and energy-efficient ones. To optimize fabric utilization and minimize fabric waste, techniques such as fully-fashioned knitting, complete garment knitting, zero-waste pattern design [248], and additive manufacturing must be compulsorily implemented across the fashion supply chain. Transportation via roads must be minimized with intelligent supply chain systems designed to reduce distribution impact. There must be a shift from internal combustion engines to electric vehicles (EVs), which are currently powered by batteries [249]. The introduction of solar fuels and hydrogen fuels that can replace fossil fuels (FFs) is necessary to decarbonize energy [246]. For the renewable transition, however, legislators must push for enforceable laws, carbon pricing schemes, funding, and state incentives [250].

The self-regulatory voluntary "Textiles 2030 Project" by WRAP aims to achieve net-zero emissions by 2050 and lower the overall carbon footprint of new clothes by 50 % compared to the 2019 levels [247,251]. These strategies must be supported by industry-standard regulations to ensure that compliance is mandatory rather than optional. Governments can play a crucial role in this shift by empowering local and regional authorities to create their circular economy strategies, aligned with globally shared goals. This approach fosters innovation and allows for tailored solutions that address specific community needs while contributing to the broader objective of sustainability [252]. The implementation of incentive-based regulatory systems can lower the upfront costs associated with implementing circular business models, and encourage suppliers to meet environmental procurement standards [215,253]. The effective use of digital technologies like AI-embedded PLMs that monitor sustainability compliance must be enhanced [254, 255]. Extensive adoption of digital technologies will help the industry develop manufacturing and consumption models that lower transportation-related environmental costs. Such technologies will make it easier to regulate and monitor labour practices in supply chains and the environmental performance of products [197].

6. Outlook of sustainable fashion

The next decade presents an opportunity for the fashion industry to achieve the urgent transformations required to avoid a climate catastrophe and the consequences thereof. As pressure builds from sustainability-conscious consumers and policymakers, the industry stands at a crossroads to fundamentally reinvent its operations around the principles of renewability, responsibility, and sufficiency [205]. Therefore, the fashion product manufacturing sector is bound to see significant investment in renewable, recycled, and biobased materials as this is projected to dominate future material flows over their synthetic counterparts [256,257]. Additionally, the industry is poised to experience strategic investments aimed at fully harnessing renewable energy and implementing zero-waste production facilities, including fully fashioned knitting and whole-garment knitting.

Furthermore, circular business models, such as clothing rental and resale platforms, are expected to gain increased popularity. Consequently, further research is essential to fully understand the

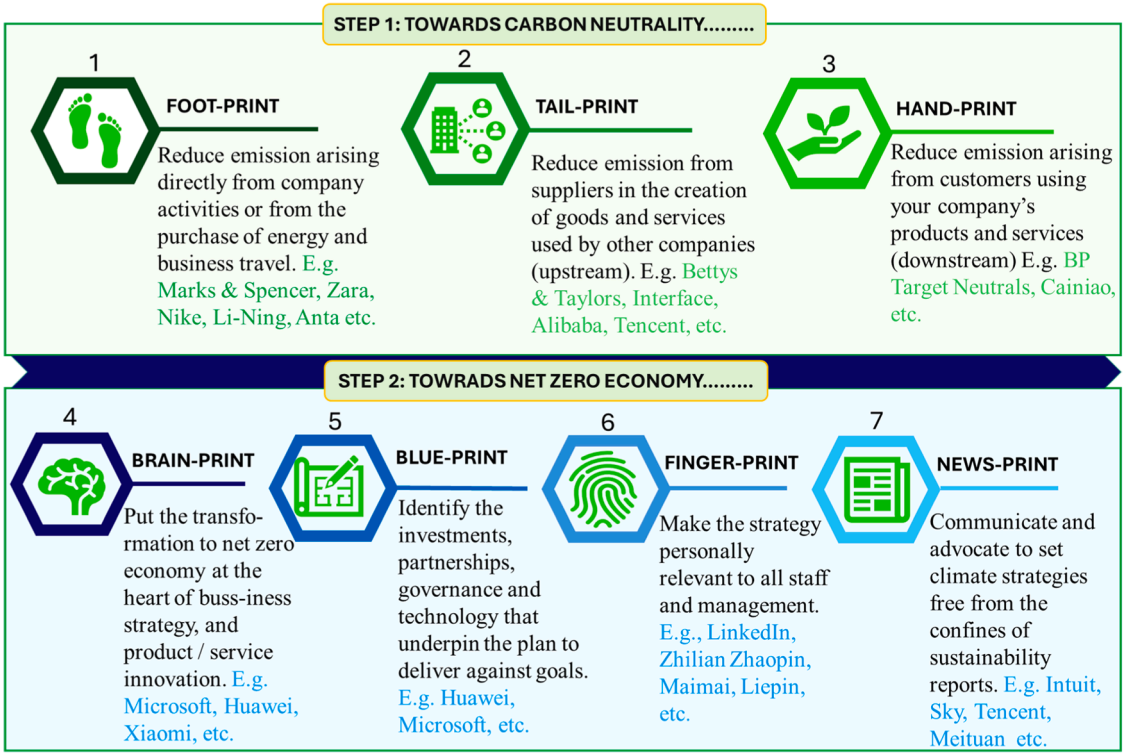

Fig. 12. The carbon neutral protocols.

sociocultural nuances of these social innovations, as the role of consumers in the journey toward a net-zero future in fashion is critical. Additionally, initiatives focused on assessing cultural trends, demographics, and geographic consumption will be vital interventions in this paradigm shift toward sustainable fashion. Moreover, as the fashion industry transitions to 5.0, digital technologies such as digital twins and autonomous manufacturing will play a crucial role in facilitating positive circular change toward sustainability [25]. Given the current capabilities of AI and the advancements in robotics for fashion production automation, garment manufacturing is set to become less labor-intensive, as robots will take over previously skilled manual tasks. Therefore, it is essential to diversify education and training in textiles and garment production to support this transition.

From a policy perspective, policymakers need to develop clear regulatory frameworks that simultaneously promote sustainability, foster economic growth, and support social equity [29]. Governments should create and enforce sustainability standards for materials and production processes, ensuring that all industry participants adhere to environmentally responsible practices. Furthermore, incentivizing sustainable practices through tax breaks or grants can motivate companies to invest in eco-friendly technologies and renewable resources [24]. This multifaceted approach will be essential for driving meaningful change within the industry. Furthermore, policies that facilitate the growth of second-hand and rental markets can significantly reduce waste and promote sustainable consumption patterns. Also, policies that encourage partnerships that share best practices for sustainable solutions will receive traction [171]. International cooperation in policy implementation is vital for addressing the global challenges posed by the fashion industry; thus, all countries, irrespective of their economic status, must collaborate to establish agreements that promote sustainable practices and reform trade policies to prioritize eco-friendly products. Such collective efforts will foster a more responsible and sustainable fashion ecosystem, benefiting both the environment and global economies. This will help create a more equitable and environmentally responsible fashion ecosystem. Furthermore, mandatory sustainability reporting for fashion companies will be required to enhance transparency and allow stakeholders to assess corporate practices effectively. Regular impact assessments will help identify areas for improvement and ensure that policies are achieving their intended outcomes. Also, the implementation of stricter environmental certifications and sustainability frameworks, facilitated by digital technologies that improve transparency and accountability in sustainability reporting is imminent. This is particularly important within the supply chain, where minimizing pollution and mitigating distribution impacts are essential. As the industry adapts to this paradigm shift toward a net-zero future, these measures will become increasingly critical.

7. Implications of sustainable fashion transition

The transition of the fashion industry towards a net zero future is a complex and multifaceted process that carries significant implications across various sectors, including academia, industry, consumers, regulators, and governments. The fashion industry's pursuit of sustainability will reshape not only business practices but also societal norms and regulatory frameworks. This shift encourages a broader cultural awareness of environmental issues, prompting consumers, brands, and policymakers to embrace more sustainable approaches in their decisions and actions. Academia plays a crucial role in the transition to a net-zero future in fashion by integrating sustainability into educational programs, thereby preparing a new generation of designers and business leaders to drive this change. Institutions that do not adapt to these evolving trends risk producing graduates who are ill-equipped to thrive in the future fashion industry. Additionally, research efforts will be geared towards the exploration of innovative materials, production methods, digital fashion technologies and consumption behaviours that reduce carbon footprint. Academics who do not adequately align with the emerging trends may face reduced research funding and output. With the increasing availability of interdisciplinary funding for sustainable fashion projects, it is crucial to foster collaboration among traditional fashion educators and experts in environmental science, computer science, mathematics, and social sciences [22,203].

For the other stakeholders in the fashion industry, the transition

toward sustainability necessitates a fundamental transformation of business models. Companies are increasingly adopting circular economy principles that focus on the entire lifecycle of products, encompassing design, production, consumption, and disposal [189,258]. This shift involves the incorporation of sustainable materials, ethical labour practices, and waste reduction strategies. This implies that fashion businesses must invest in sustainable technologies and ensure supply chain transparency. In the years ahead, brands that effectively embrace sustainability can gain a competitive advantage, as consumers are increasingly drawn to companies that demonstrate environmental responsibility. This shift will not only meet consumer demand but also cultivate long-term brand loyalty, driven by heightened consumer awareness of environmental issues that ultimately influence their sustainable choices [68]. This change will be reflected in the rising demand for eco-friendly products, second-hand clothing, and rental services. This awareness will subsequently extend beyond mere purchasing habits and will result in more advocacy for change, pressuring brands to adopt sustainable practices. This evolving consumer landscape requires companies to engage in transparent communication and foster trust with their audiences, as consumers seek authenticity in their purchasing decisions.

Governments and international organizations are progressively enacting policies and regulations designed to mitigate the environmental impact of the fashion industry. Initiatives such as carbon pricing, waste management regulations, and incentives for sustainable practices [207] are bound to expand. To this end, collaboration between regulators and industry is essential for the development of standards that promote sustainability while fostering innovation.

7.1. Summary of the pathway towards net zero-future fashion

The transition towards a net zero future in the fashion industry presents profound implications across industry, consumers, regulators, and governments. As each sector navigates this complex landscape, collaboration, and innovation will be crucial in driving meaningful change. A summary of the pathway for transitioning to a net-zero future is illustrated in Fig. 13 and discussed briefly. This pathway involves a comprehensive approach that integrates sustainability across all facets of production and consumption. This journey begins with sustainable materials innovations, such as organic and recycled fabrics, which reduce reliance on virgin resources and minimize environmental impact. Collaboration among stakeholders including manufacturers, retailers, policymakers, and consumers is essential.

Policymakers play a crucial role in establishing regulatory frameworks that enforce sustainability standards and incentivize eco-friendly practices. Concurrently, industry players must invest in innovative technologies that enhance efficiency and reduce emissions throughout the supply chain. Consumer engagement is also pivotal; educating consumers about sustainable choices can drive demand for responsible fashion. Ultimately, achieving a net-zero future in fashion requires a collective commitment to rethinking business practices, fostering innovation, and prioritizing environmental stewardship at every level of the industry.

7.2. Limitations of the study

Despite the robust methodology adopted for this review, the authors acknowledge the retrospective nature of the data collection, hence, the recentness and applicability may be limited by the issue of time lag caused by a clear cut-off date for study inclusion. Also, the results were mostly dependent on the accessibility and availability of pertinent scientific literature from SDB. Moreover, we employed a wide range of terms and synonyms in our literature search on Scopus. However, we acknowledge the inherent limitations of this approach, as varying combinations of terms and synonyms could potentially yield a broader spectrum of relevant documents. Additionally, only papers written in the English language were chosen for inclusion even though other databases than English exist. Due to these and numerous other unanticipated circumstances, the geographic alliances and study results by states, people, and organizations may not be overtly conclusive.

8. Conclusion

The fashion industry is increasingly recognizing the imperative of setting net-zero targets as a critical response to climate change, aligning its efforts with the Sustainable Development Goals (SDGs). Achieving net-zero emissions requires a comprehensive approach that encompasses sustainable sourcing, innovative production methods, and responsible consumption practices. SDG 12, which emphasizes responsible consumption and production, the industry can minimize waste and promote circular economy principles. Furthermore, aligning with SDG 13, which calls for urgent climate action, the sector can implement strategies to reduce greenhouse gas emissions throughout the supply chain. Collaborative efforts among stakeholders including brands,

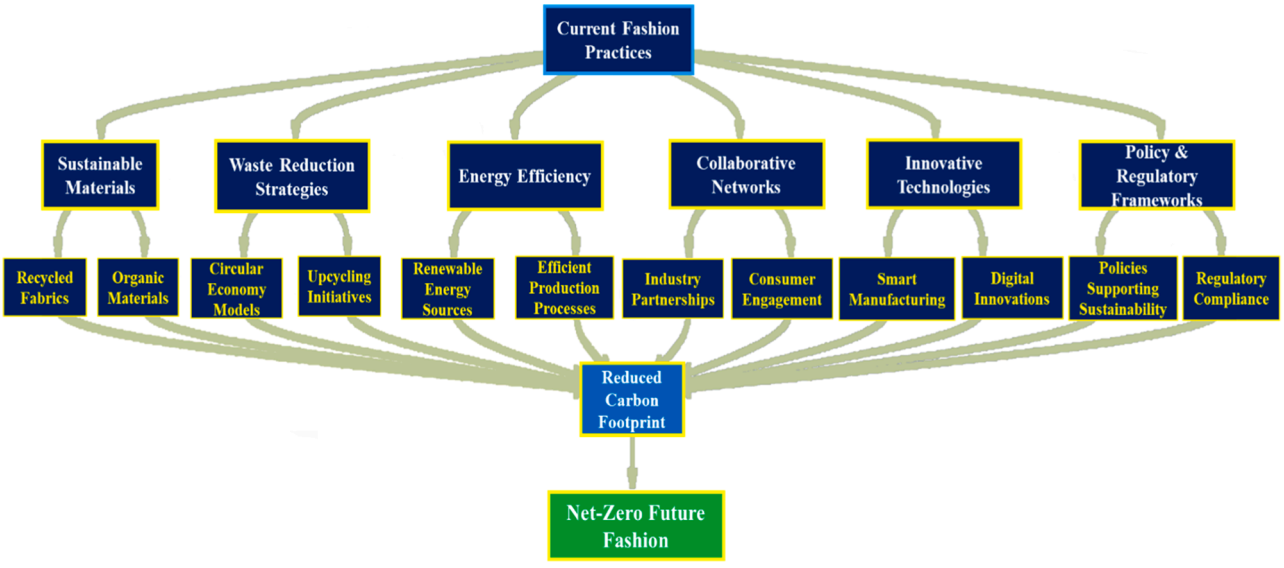

Fig. 13. Summary of the pathway towards net-zero transition by the fashion industry.

policymakers, and consumers are essential to drive meaningful change and ensure that sustainable practices are embedded within the industry's framework. Ultimately, the commitment to net-zero targets not only addresses environmental challenges but also fosters social equity, aligning with SDG 8′s focus on decent work and economic growth, thereby contributing to a more sustainable and equitable future for all. Academically, most of the initiatives have resulted in an exponential increase in research output over the last decade. Collaboration is recognized as an important catalyst for the transition to a net-zero future due to the concerted effort by policymakers, industry players, scholars, and the public. The findings point to a fast-paced transition to more sustainable practices in materials innovations and production processes fuelled by digital technologies such as AI, blockchain, extended reality, and IoT as well as social innovations, and circular models. These and many other novel initiatives have the potential to lower energy demands and curb the rate of pollution, which will go a long way to contribute to brand loyalty, good ethics, and societal, environmental, and economic benefits. This review puts in perspective the existing body of knowledge on sustainable fashion and provides succinct information on the transition to a net-zero future fashion as envisioned by the "Fashion Pact 2050″.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used the QuilBot free version for language editing and paraphrasing. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Benjamin Tawiah: Software, Writing – original draft, Formal analysis, Writing – review & editing, Data curation. **Erin Cho:** Writing – review & editing, Validation, Project administration, Formal analysis. **Emmanuel A. Ofori:** Investigation, Writing – original draft, Software, Formal analysis. **Minyoung Suh:** Writing – review & editing, Investigation, Writing – original draft, Formal analysis. **Bin Fei:** Writing – review & editing, Project administration, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Data availability

No data was used for the research described in the article.

References

[1] S. Khan, A. Malik, Environmental and health effects of textile industry wastewater, Environ. Deterior. Hum. Health:. Nat. Anthropog. Determ. (2014) 55–71.
[2] T. Sarwar, S. Khan, Textile industry: pollution health risks and toxicity, in: Textile Wastewater Treatment: Sustainable Bio-Nano Materials and Macromolecules, 1, Springer, 2022, pp. 1–28.
[3] A.A. Khalifa, et al., Accelerating the transition to a circular economy for net-zero emissions by 2050: a systematic review, Sustainability 14 (18) (2022) 11656.
[4] M. Sadowski, L. Perkins, E. McGarvey, Roadmap to Net zero: Delivering Science-Based Targets in the Apparel Sector, World Resources Institute, Washington, DC, USA, 2021.
[5] P. Kautish, A. Khare, R. Sharma, Values, sustainability consciousness and intentions for SDG endorsement, Mark. Intell. Plan. 38 (7) (2020) 921–939.
[6] N. Radclyffe-Thomas, Sustainable development and the aspirational male consumer: tengri, making the case for sustainable luxury, Crit. Stud. Men's. Fash. 8 (1–2) (2021) 245–266.
[7] B. Pan, The Wicked Problem. Accelerating Sustainability in Fashion, Clothing and Textiles, Routledge, 2023, pp. 39–51.
[8] C.-L. Hsieh, W.-H. Tsai, Sustainable decision model for circular economy towards net zero emissions under industry 4.0, Processes 11 (12) (2023) 3412.
[9] K. Govindan, How digitalization transforms the traditional circular economy to a smart circular economy for achieving SDGs and net zero, Transp. Res. E:. Logist. Transp. Rev. 177 (2023) 103147.
[10] R. Roy, et al., Sustainable manufacturing practices in textiles and fashion. Sustainable Manufacturing Practices in the Textiles and Fashion Sector, Springer, 2024, pp. 1–22.
[11] E. Quintana, C. Valls, M.B. Roncero, Dissolving-grade pulp: a sustainable source for fiber production, Wood. Sci. Technol (2024) 1–63.
[12] C.E. Henninger, et al., Cradle-to-cradle versus consumer preferences in the fashion industry. Encyclopaedia of Renewable and Sustainable Materials, Elsevier, Oxford, 2020, pp. 353–357.
[13] M.T. Hossain, et al., Techniques, applications, and challenges in textiles for sustainable future, J. Open. Innov.: Technol. Mark. Complex. (2024) 100230.
[14] A.M. Thakker, D. Sun, Sustainable development goals for textiles and fashion, Environ. Sci. Pollut. Res. 30 (46) (2023) 101989–102009.
[15] E. Eppinger, Recycling technologies for enabling sustainability transitions of the fashion industry: status quo and avenues for increasing post-consumer waste recycling, Sustain.:. Sci. Pract. Policy 18 (1) (2022) 114–128.
[16] P. Kautish, S. Guru, A. Sinha, Values, satisfaction and intentions: online innovation perspective for fashion apparels, Int. J. Innov. Sci. 14 (3/4) (2022) 608–629.
[17] A.S.M. Sayem, Digital Fashion Innovations For the Real World and Metaverse, Taylor & Francis, 2022, pp. 139–141.
[18] A. Kozlowski, C. Searcy, M. Bardecki, Innovation for a sustainable fashion industry: a design focused approach toward the development of new business models, Green. Fash. 2 (2016) 151–169.
[19] S. Garcia-Torres, et al., Traceability and transparency for sustainable fashion-apparel supply chains, J. Fash. Mark. Manag.:. Int. J. 26 (2) (2022) 344–364.
[20] A. Brun, H. Karaosman, T. Barresi, Supply chain collaboration for transparency, Sustainability 12 (11) (2020) 4429.
[21] A. Paço, et al., Fostering sustainable consumer behavior regarding clothing: assessing trends on purchases, recycling and disposal, Text. Res. J. 91 (3–4) (2021) 373–384.
[22] M. Peleg Mizrachi, A. Tal, Regulation for promoting sustainable, fair and circular fashion, Sustainability 14 (1) (2022) 502.
[23] R. Earley, Clothing 2050: garment scenarios to drive circular material systems. Accelerating Sustainability in Fashion, Clothing and Textiles, Routledge, 2023, pp. 191–202.
[24] V. Jacometti, Circular economy and waste in the fashion industry, Laws 8 (4) (2019) 27.
[25] C.H. dos Santos, et al., Decision-making in a fast fashion company in the Industry 4.0 era: a Digital Twin proposal to support operational planning, Int. J. Adv. Manuf. Technol. 116 (2021) 1653–1666.
[26] M.D. Alam, G. Kabir, S. Mirmohammadsadeghi, A digital twin framework development for apparel manufacturing industry, Decis. Anal. J. 7 (2023) 100252.
[27] N.Y. Konina, Smart digital innovations in the global fashion industry and a climate change action plan. Smart Green Innovations in Industry 4.0 For Climate Change Risk Management, Springer, 2023, pp. 255–263.
[28] B. Rathore, Fashion sustainability in the AI era: opportunities and challenges in marketing, Eduzone:. Int. Peer. Rev./Ref. Multidiscip. J. 8 (2) (2019) 17–24.
[29] A. Pastran, E. Colli, H.M. Nor, Public policy and legislation in sustainable fashion, Sustain. Fash. Text. Lat. Am. (2021) 171–189.
[30] Pelkmans, J. and A. Renda, *Does EU regulation hinder or stimulate innovation?* 2014.
[31] P.H. Huynh, Enabling circular business models in the fashion industry: the role of digital innovation, Int. J. Product. Perform. Manag. 71 (3) (2022) 870–895.
[32] M.J. Page, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, Bmj 372 (2021).
[33] R. Pranckutė, Web of Science (WoS) and Scopus: the titans of bibliographic information in today's academic world, Publications 9 (1) (2021) 12.
[34] N.J. van Eck, L. Waltman, Software survey: vOSviewer, a computer program for bibliometric mapping, Scientometrics 84 (2) (2010) 523–538.
[35] M. Aria, C. Cuccurullo, bibliometrix: an R-tool for comprehensive science mapping analysis, J. Inf. 11 (4) (2017) 959–975.
[36] B. Tawiah, E.A. Ofori, F. Bin, Scientometric review of sustainable fire-resistant polysaccharide-based composite aerogels, Sustainability 15 (16) (2023) 12185.
[37] J. Orminski, E.C. Tandoc Jr, B.H. Detenber, #sustainablefashion – A conceptual framework for sustainable fashion discourse on Twitter, Environ. Commun. 15 (1) (2021) 115–132.

[38] M. Durrani, People gather for Stranger Things, so why not this?" learning sustainable sensibilities through communal garment-mending practices, Sustainability 10 (2018), https://doi.org/10.3390/su10072218.
[39] R.K. Seidu, B. Eghan, R. Acquaye, A review of circular fashion and bio-based materials in the fashion industry, Circ. Econ. Sustain. (2023).
[40] L.M. Degenstein, R.H. McQueen, N.T. Krogman, What goes where'? Characterizing Edmonton's municipal clothing waste stream and consumer clothing disposal, J. Clean. Prod 296 (2021) 126516.
[41] L. Coscieme, et al., A framework of circular business models for fashion and textiles: the role of business-model, technical, and social innovation, Sustain.:. Sci. Pract. Policy 18 (1) (2022) 451–462.
[42] S. Mukherjee, Environmental and social impact of fashion: towards an eco-friendly, ethical fashion, Int. J. Interdiscip. Multidiscip. Stud. 2 (3) (2015) 22–35.
[43] S. Plakantonaki, et al., A review of sustainability standards and ecolabeling in the textile industry, Sustainability 15 (2023), https://doi.org/10.3390/su151511589.
[44] E.A. Skinner, et al., #sustainablefashion on Instagram: a content and network analysis of user-generated posts, J. Consum. Behav. 22 (5) (2023) 1096–1111.
[45] H.J. Park, L.M. Lin, Exploring attitude–behavior gap in sustainable consumption: comparison of recycled and upcycled fashion products, J. Bus. Res 117 (2020) 623–628.
[46] K. Niinimäki, et al., The environmental price of fast fashion, Nat. Rev. Earth. Environ. 1 (4) (2020) 189–200.
[47] T. Brydges, Closing the loop on take, make, waste: investigating circular economy practices in the Swedish fashion industry, J. Clean. Prod 293 (2021) 126245.
[48] D.G.K. Dissanayake, D. Weerasinghe, Towards circular economy in fashion: review of strategies, barriers and enablers, Circ. Econ. Sustain. 2 (1) (2022) 25–45.
[49] P. Olatubosun, E. Charles, T. Omoyele, Rethinking luxury brands and sustainable fashion business models in a risk society, J. Des. Bus. Soc. 7 (1) (2021) 49–81.
[50] U. Golob, et al., Brand management and sustainability: exploring potential for the transformative power of brands, J. Brand. Manag. 29 (6) (2022) 513–519.
[51] S. Sarker, B. Istvan, A bibliometric review of green technology- related research in the textile industry, Text. Leather. Rev. 6 (2023) 813–836.
[52] Jhanji, Y. *Design & development of sustainable embellished fashion ensembles for alpha women*. 2023.
[53] H. Pui-Yan Ho, T.M. Choi, A five-R analysis for sustainable fashion supply chain management in Hong Kong: a case analysis, J. Fash. Mark. Manag.:. Int. J. 16 (2) (2012) 161–175.
[54] O. Rahman, M. Koszewska, A study of consumer choice between sustainable and non-sustainable apparel cues in Poland, J. Fash. Mark. Manag.:. Int. J. (2020) **ahead-of-print**.
[55] P. Bertola, J. Teunissen, Fashion 4.0. Innovating fashion industry through digital transformation, Res. J. Text. Appar. 22 (4) (2018) 352–369.
[56] M. Martin, F. Vacca, Heritage narratives in the digital era: how digital technologies have improved approaches and tools for fashion know-how, traditions, and memories, Res. J. Text. Appar. 22 (4) (2018) 335–351.
[57] S.-Y. Liu, G.-X. Yuan, The virtual fashion in the global apparel industry in the post-epidemic era, J. Fiber. Bioeng. Inform. 15 (2) (2022) 117–130.
[58] H. Lee, K. Leonas, Consumer experiences, the key to survive in an omni-channel environment: use of virtual technology, J. Text. Appar. Technol. Manag. 10 (3) (2018).
[59] B. Silvestri, The future of fashion: how the quest for digitization and the use of artificial intelligence and extended reality will reshape the fashion industry after COVID-19, ZoneModa. J. 10 (2) (2020) 61–73.
[60] J. Kim, S. Forsythe, Adoption of virtual try-on technology for online apparel shopping, J. Interact. Mark. 22 (2) (2008) 45–59.
[61] Costello, M.J., *ARCAD: augmented reality computer aided design*. 2018.
[62] J. Lewis, The New Costume designer: an Exploration of Digital and Physical Technologies For Costume Development in the Film industry: an Exegesis Presented in Partial Fulfilment of the Requirements For the Degree of Master of Design, Massey University, College of Creative Arts, Wellington, New Zealand, Massey University, 2019.
[63] Slemang, Z., *Sense of style: constructing identity and managing impressions on Lookbook. nu*. 2016.
[64] G. Killian, K. McManus, A marketing communications approach for the digital era: managerial guidelines for social media integration, Bus. Horiz 58 (5) (2015) 539–549.
[65] D. Casciani, O. Chkanikova, R. Pal, Exploring the nature of digital transformation in the fashion industry: opportunities for supply chains, business models, and sustainability-oriented innovations, Sustain.:. Sci. Pract. Policy 18 (1) (2022) 773–795.
[66] H. McCormick, et al., Fashion retailing–past, present and future, Text. Prog. 46 (3) (2014) 227–321.
[67] P.A. Marques, D. Jorge, J. Reis, Using lean to improve operational performance in a retail store and e-commerce service: a Portuguese case study, Sustainability 14 (10) (2022) 5913.
[68] A. Shrivastava, et al., Sustainability through online renting clothing: circular fashion fueled by instagram micro-celebrities, J. Clean. Prod 278 (2021) 123772.
[69] A. Shamsuzzoha, et al., Dynamic and collaborative business networks in the fashion industry, Int. J. Comput. Integr. Manuf. 26 (1–2) (2013) 125–139.
[70] L. Sun, L. Zhao, Technology disruptions: exploring the changing roles of designers, makers, and users in the fashion industry, Int. J. Fash. Des. Technol. Educ. 11 (3) (2018) 362–374.
[71] M. Li, L. Zhao, Exploring global fashion sustainability practices through dictionary-based text mining, Cloth. Text. Res. J. 41 (3) (2023) 175–190.
[72] B. Rathore, Beyond trends: shaping the future of fashion marketing with AI, sustainability and machine learning, Eduzone 6 (2) (2017) 16–24.
[73] B. Rathore, AI and the future of ethical fashion marketing: a comprehensive analysis of sustainable methods and consumer engagement, Eduzone 5 (2) (2016) 14–24.
[74] M.-K. Petrasch, The Physicality of AI and Its Meaning For Sustainable AI: A Discussion of Sustainable AI for Sustainable Fashion and How to Approach it, University of Twente, 2022.
[75] S.V. Akram, et al., Implementation of digitalized technologies for fashion industry 4.0: opportunities and challenges, Sci. Program 2022 (2022).
[76] M. Ghoreishi, K. Bhandari, A. Franconi, Smart fashion economy through a data-driven circular ecosystem: a case study, in: IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2022.
[77] Y.K. Lee, Transformation of the innovative and sustainable supply chain with upcoming real-time fashion systems, Sustainability 13 (3) (2021) 1081.
[78] A.M. Pereira, et al., Customer models for artificial intelligence-based decision support in fashion online retail supply chains, Decis. Support. Syst 158 (2022) 113795.
[79] Evangelista, P.N., *Artificial intelligence in fashion: how consumers and the fashion system are being impacted by AI-powered technologies*. 2020.
[80] N. Arora, B. Anant, K. Chaudhary, Optimizing supply chains in the fashion & textile industry through AI, INCFAT 23 (2023) 61.
[81] Reine, R., et al., *Cyber-physical-social systems: an overview*. Smart Connected World: Technologies and Applications Shaping the Future, 2021: p. 25–45.
[82] J. Qiu, L. Ma, Fusion mode and style based on artificial intelligence and clothing design, Math. Probl. Eng. 2021 (2021) 1–16.
[83] M. Mohiuddin Babu, et al., The role of artificial intelligence in shaping the future of agile fashion industry, Prod. Plan. Control (2022) 1–15.
[84] D'Itria, E. and C. Colombi *Biobased innovation as a fashion and textile design must: a European perspective*. Sustainability, 2022. 14, DOI: 10.3390/su14010570.
[85] K. Shirvanimoghaddam, et al., Death by waste: fashion and textile circular economy case, Sci. Total. Environ. 718 (2020) 137317.
[86] M. Lebedytė, D. Sun, A review: can waste wool keratin be regenerated as a novel textile fibre via the reduction method? J. Text. Inst. 113 (8) (2022) 1750–1766.
[87] S. Aboughe-Angone, et al., Plant cell wall polysaccharides: immunomodulators of the immune system and source of natural fibers, Phytochemistry 20 (2011) 1–16.
[88] A. Bochek, Prospects for use of polysaccharides of different origin and environmental problems in processing them, Fibre. chem. 40 (3) (2008) 192–197.
[89] Y.-A. Lee, Leading Edge Technologies in Fashion Innovation, Springer, 2022.
[90] M. Mochizuki, et al., 8 - Synthesis, properties and structure of polylactic acid fibres, in: S.J. Eichhorn, et al. (Eds.), Handbook of Textile Fibre Structure, Woodhead Publishing, 2009, pp. 257–275. Editors.
[91] F.G. Torres, et al., Natural polysaccharide nanomaterials: an overview of their immunological properties, Int. J. Mol. Sci (20) (2019) 20.
[92] L.D. Burns, K.K. Mullet, N.O. Bryant, The Business of fashion: Designing, manufacturing, and Marketing, Bloomsbury Publishing USA, 2016.
[93] X. Zhao, et al., Recent progress of preparation of branched poly (lactic acid) and its application in the modification of polylactic acid materials, Int,. J. Biol,. Macromol 193 (2021) 874–892.
[94] B. Tawiah, B. Yu, B. Fei, Advances in flame retardant poly (lactic acid), Polym. (Basel) 10 (8) (2018) 876.
[95] Y. Zhou, et al., A facile and sustainable approach for simultaneously flame retarded, UV protective and reinforced poly (lactic acid) composites using fully bio-based complexing couples, Compos. B:. Eng. 215 (2021) 108833.
[96] F. Asabuwa Ngwabebhoh, et al., Bio-innovation of new-generation nonwoven natural fibrous materials for the footwear industry: current state-of-the-art and sustainability panorama, J. Nat. Fibers 19 (13) (2022) 4897–4907.
[97] E.R.K.B. Wijayarathna, et al., Fungal textile alternatives from bread waste with leather-like properties, Resour. Conserv. Recycl. 179 (2022) 106041.
[98] R. Sehgal, R. Gupta, Polyhydroxyalkanoate and its efficient production: an eco-friendly approach towards development, 3, Biotech 10 (12) (2020) 549.
[99] J. Domskiene, F. Sederavičiūtė, J. Simonaityte, Kombucha bacterial cellulose for sustainable fashion, Int. J. Cloth. Sci. Technol. 31 (2019).
[100] H.N. Phan, N.K. Vu, H.M. Bui, Fabrication and characterization of patterned leather-like biomaterial derived from Brazilein/glycerol-finished bacterial cellulose by using 3-in-1 textile finishing process, Cellulose 30 (8) (2023) 5217–5237.
[101] A. Amobonye, et al., Fungal mycelium as leather alternative: a sustainable biogenic material for the fashion industry, Sustain. Mater. Technol. 38 (2023) e00724.
[102] GrandResearchStore, Global mushroom leather market [cited 2024 March 27]; Available from: https://www.grandresearchstore.com/, 2023.
[103] J. Hildebrandt, D. Thrän, A. Bezama, The circularity of potential bio-textile production routes: comparing life cycle impacts of bio-based materials used within the manufacturing of selected leather substitutes, J. Clean. Prod 287 (2021) 125470.
[104] A. Amobonye, et al., Fungal mycelium as leather alternative: a sustainable biogenic material for the fashion industry, Sustain. Mater. Technol. (2023) e00724.
[105] J. Raman, et al., Mycofabrication of mycelium-based leather from brown-Rot fungi, J. Fungi. (Basel) 8 (3) (2022).
[106] L. Rahme, Fish skin, a sustainable material used from ancient times to today's fashion, FormAkademisk. -. forskningstidsskrift. des. des. 14 (2021).
[107] Europages, COMPANIES - SUPPLIERS - SERVICE PROVIDERS fish-leather [cited 2024 March 27]; Available from: https://www.europages.co.uk/companies/fish-leather.html, 2019.

[108] StraitResearch, Fish Leather Market [cited 2024 March 27]; Available from: https://straitsresearch.com/report/fish-leather-market, 2024.
[109] K.T. Chaka, Beneficiation of textile spinning waste: production of nonwoven materials, J. Nat. Fibers 19 (14) (2022) 9064–9073.
[110] S.E. Svensson, et al., Fungal textiles: wet spinning of fungal microfibers to produce monofilament yarns, Sustain. Mater. Technol. 28 (2021) e00256.
[111] C. Aumnate, et al., Polylactic acid/kenaf cellulose biocomposite filaments for melt extrusion based-3D printing, Cellulose 28 (13) (2021) 8509–8525.
[112] R. Earley, Sustainable textiles for fashion, J. Phys.:. Mater. 5 (032001) (2022) 81–84.
[113] P. Pandit, T. Gayatri, S. Maiti, Green and sustainable textile materials using natural resources, Green. Sustain. Adv. Mater. Process. Charact 1 (2018) 213–261.
[114] D.W.-S. Suen, et al., Sustainable textile raw materials: review on bioprocessing of textile waste via electrospinning, Sustainability 15 (15) (2023) 11638.
[115] R. Nayak, et al., A review of recent trends in sustainable fashion and textile production, Workforce 13 (2019) 11–12.
[116] B. Pizzicato, et al., Advancements in sustainable natural dyes for textile applications: a review, Molecules 28 (16) (2023) 5954.
[117] A.P. Periyasamy, J. Militky, Sustainability in textile dyeing: recent developments, Sustain. Text. Appar. Ind.: Prod. Process. Sustain. (2020) 37–79.
[118] A.F. Halim, M.T. Islam, M.M.U. Hoque, Chemistry of sustainable coloration of textile materials. Green Chemistry for Sustainable Textiles, Elsevier, 2021, pp. 57–67.
[119] R. Jamee, R. Siddique, Biodegradation of synthetic dyes of textile effluent by microorganisms: an environmentally and economically sustainable approach, Eur. J. Microbiol. Immunol. 9 (4) (2019) 114–118.
[120] K. Nakpan, S. Sirinkraporn, Amplituhedron: a bio-melanin fibre synthesized from soil bacteria for the design of innovative sustainable garments, Des. J. 26 (2) (2023) 290–309.
[121] F. Bell, E. McQuaid, M. Alistar, Alganyl: cocinando ropa sustentable, Rev. Diseña (2022).
[122] J. Levec, Oxidation of an azo dye in subcritical aqueous solutions, Ind. Eng. Chem. Res 36 (9) (1997) 3480–3486.
[123] M. Banchero, Recent advances in supercritical fluid dyeing, Color. Technol. 136 (4) (2020) 317–335.
[124] M. Mohsin, S. Sardar, Multi-criteria decision analysis for textile pad-dyeing and foam-dyeing based on cost, performance, productivity and sustainability, Cellulose 26 (6) (2019) 4143–4157.
[125] I. Mahmud, S. Kaiser, Recent progress in waterless textile dyeing, J. Text. Sci. Eng 10 (6) (2020) 1–3.
[126] K. Schmidt-Przewozna, E. Rój, Green sustainable textile supercritical dyeing process using CO2 madder (Rubia tinctorum L.) extract, J. Nat. Fibers 20 (2) (2023) 2277836.
[127] L. Chen, et al., Hydrolysis-free and fully recyclable reactive dyeing of cotton in green, non-nucleophilic solvents for a sustainable textile industry, J. Clean. Prod 107 (2015) 550–556.
[128] R. Gupta, V. Shukla, P. Agarwal, Sustainable transformation in modest fashion through "RPET technology" and "dry-dye" process, using recycled PET Plastic, Int. J. Recent. Technol. Eng. 8 (2019) 515–5421.
[129] S. Shatarah, Eco-dyeing techniques in sustainable fashion: a comprehensive analysis of natural and low-impact dyeing methods, Kurd. Stud. 12 (2) (2024) 4222–4231.
[130] Arunraj, A., et al., *Sustainable dyeing techniques: advancements and innovations in the textile industry*.
[131] Black, S., *Sustainability and digitalization.* 2019.
[132] D. Dissanayake, Does mass customization enable sustainability in the fashion industry, in: R. Belatramo, A. Romani, P. Cantore (Eds.), Fashion Industry-An Itinerary Between Feelings and Technology, 2019, pp. 21–32. Eds.
[133] G. McMullan, et al., Microbial decolourisation and degradation of textile dyes, Appl,. Microbiol,. Biotechnol 56 (1) (2001) 81–87.
[134] H. Patel, et al., A recent and systemic approach towards microbial biodegradation of dyes from textile industries, Water. (Basel) 14 (19) (2022) 3163.
[135] S. Varjani, et al., Microbial degradation of dyes: an overview, Bioresour,. Technol 314 (2020) 123728.
[136] S.K. Garg, M. Tripathi, Microbial strategies for discoloration and detoxification of azo dyes from textile effluents, Res. J. Microbiol 12 (1) (2017) 1–19.
[137] M. Solís, et al., Microbial decolouration of azo dyes: a review, Process. Biochem. 47 (12) (2012) 1723–1748.
[138] H.H. Sornaly, et al., The utility of bioremediation approach over physicochemical methods to detoxify dyes discharges from textile effluents: a comprehensive review study, Sustain. Chem. Pharm. 39 (2024) 101538.
[139] A.V. Sonawane, et al., A review of microbial fuel cell and its diversification in the development of green energy technology, Chemosphere 350 (2024) 141127.
[140] M.F. Lanjwani, et al., Trends in photocatalytic degradation of organic dye pollutants using nanoparticles: a review, Inorg. Chem. Commun 159 (2024) 111613.
[141] A. Iqbal, et al., Insight into the degradation of different classes of dyes by advanced oxidation processes; a detailed review, Int. J. Env. Anal. Chem (2023) 1–35.
[142] T. Wu, et al., TiO2-assisted photodegradation of dyes. 9. Photooxidation of a squarylium cyanine dye in aqueous dispersions under visible light irradiation, Env.,. Sci,. Technol 33 (9) (1999) 1379–1387.
[143] L. Lianmawii, et al., A review: photocatalytic degradation of dyes by metal sulfide nanoparticles, Braz. J. Chem. Eng. (2024).
[144] W.S. Koe, et al., An overview of photocatalytic degradation: photocatalysts, mechanisms, and development of photocatalytic membrane, Environ. Sci. Pollut. Res. 27 (3) (2020) 2522–2565.
[145] D. Ayodhya, G. Veerabhadram, A review on recent advances in photodegradation of dyes using doped and heterojunction based semiconductor metal sulfide nanostructures for environmental protection, Mater. today. energy 9 (2018) 83–113.
[146] L. Lianmawii, et al., A review: photocatalytic degradation of dyes by metal sulfide nanoparticles, Braz. J. Chem. Eng. (2024) 1–30.
[147] J. Lin, et al., Sustainable management of textile wastewater: a hybrid tight ultrafiltration/bipolar-membrane electrodialysis process for resource recovery and zero liquid discharge, Ind. Eng. Chem. Res 58 (25) (2019) 11003–11012.
[148] A. Culcasi, et al., A comprehensive multi-scale model for bipolar membrane electrodialysis (BMED), Chem. Eng. J. 437 (2022) 135317.
[149] A. Gangoda, S. Krasley, K. Cobb, AI digitalisation and automation of the apparel industry and human workforce skills, Int. J. Fash. Des. Technol. Educ. 16 (3) (2023) 319–329.
[150] B.E. Jin, D.C. Shin, The power of 4th industrial revolution in the fashion industry: what, why, and how has the industry changed? Fash. Text. 8 (1) (2021) 31.
[151] S. Mingyoung, Automated cutting and sewing for Industry 4.0, Text. World (2024).
[152] M. Salahuddin, Y.-A. Lee, Automation with robotics in garment manufacturing. Leading Edge Technologies in Fashion Innovation: Product Design and Development Process from Materials to the End Products to Consumers, Springer, 2022, pp. 75–94.
[153] S. Mingyoung, Automated cutting & sewing developments. Textile World, Textile World, 2020.
[154] E. Papachristou, D. Kalaitzi, V. Pissas, A methodological framework for the integration of 3D virtual prototyping into the design development of laser-cut garments, J. Eng. Fiber. Fabr 18 (2023) 15589250231194621.
[155] G.X. Yuan, et al., Application of laser engraving for sustainable fashion design, Res. J. Text. Appar. 17 (2) (2013) 21–27.
[156] M. Ahmad, D. Sun, T. Hussain, A perspective on seamless woven garments, J. Nat. Fibers 20 (2) (2023) 2265568.
[157] Z. Xue, Z. Huang, Current development and future prospects of designing sustainable fashion, Autex. Res. J. 23 (3) (2023) 420–431.
[158] N.A. Ibrahim, et al., A green approach for modification and functionalization of wool fabric using bio- and nano-technologies, Clean. Technol. Environ. Policy 24 (10) (2022) 3287–3302.
[159] L. Lara, I. Cabral, J. Cunha, Ecological approaches to textile dyeing: a review, Sustainability 14 (2022), https://doi.org/10.3390/su14148353.
[160] T. Toprak-Cavdur, A novel and integrated approach to dyeing recycled cotton and Chitosan yarns blended fabrics with innovative nanobubble technology, Fibers. Polym. 24 (11) (2023) 3969–3978.
[161] N. Meksi, A. Moussa, A review of progress in the ecological application of ionic liquids in textile processes, J. Clean. Prod 161 (2017) 105–126.
[162] A. Hasanbeigi, L. Price, A review of energy use and energy efficiency technologies for the textile industry, Renew. Sustain. Energy. Rev. 16 (6) (2012) 3648–3665.
[163] A. Hasanbeigi, L. Price, A technical review of emerging technologies for energy and water efficiency and pollution reduction in the textile industry, J. Clean. Prod 95 (2015) 30–44.
[164] B.S. Reddy, B.K. Ray, Understanding industrial energy use: physical energy intensity changes in Indian manufacturing sector, Energy. Policy 39 (11) (2011) 7234–7243.
[165] K. Farhana, et al., Energy consumption, environmental impact, and implementation of renewable energy resources in global textile industries: an overview towards circularity and sustainability, Mater. Circ. Econ. 4 (1) (2022) 15.
[166] T. Mitrova, Y. Melnikov, Energy transition in Russia, Energy. Transit. 3 (1) (2019) 73–80.
[167] S. Kousar, et al., Sustainable energy consumption model for textile industry using fully intuitionistic fuzzy optimization approach, Comput. Intell. Neurosci 2022 (2022) 5724825.
[168] M.J.B. Kabeyi, O.A. Olanrewaju, Sustainable energy transition for renewable and low carbon grid electricity generation and supply, Front. Energy. Res. 9 (2022).
[169] M. Colla, A. Ioannou, G. Falcone, Critical review of competitiveness indicators for energy projects, Renew. Sustain. Energy. Rev. 125 (2020) 109794.
[170] M. Meskini, et al., Sustainability, profitability, and resiliency of the fast fashion industries during a pandemic, Energy. Environ. (2024), p. 0958305X241239896.
[171] R. Vijeyarasa, M. Liu, Fast fashion for 2030: using the pattern of the Sustainable Development Goals (SDGs) to cut a more gender-just fashion sector, Bus. Hum. Rights. J. 7 (1) (2022) 45–66.
[172] A. Mukendi, et al., Sustainable fashion: current and future research directions, Eur. J. Mark 54 (11) (2020) 2873–2909.
[173] C. Diep, Awareness of the term "sustainable fashion" in Japan as ofOctober 2024, by age [cited 2025 March]; Available from: https://www.statista.com/statistics/1412891/japan-awareness-sustainable-fashion-by-age/, 2024.
[174] T. Bianchi, Leading sustainable fashion brands worldwide 2020-2023, by monthly searches, Statista (2023).
[175] C.M. Armstrong, et al., A use-oriented clothing economy? Preliminary affirmation for sustainable clothing consumption alternatives, Sustain. Dev. 24 (1) (2016) 18–31.
[176] H. Hong, J.H. Kang, The impact of moral philosophy and moral intensity on purchase behavior toward sustainable textile and apparel products, Fash. Text. 6 (1) (2019) 16.

[177] K.S. Nielsen, W. Hofmann, Motivating sustainability through morality: a daily diary study on the link between moral self-control and clothing consumption, J. Env. Psychol 73 (2021) 101551.
[178] M. Koszewska, A typology of Polish consumers and their behaviours in the market for sustainable textiles and clothing, Int. J. Consum. Stud 37 (5) (2013) 507–521.
[179] A. Choudhary, et al., A greener world through Collaborative consumption of Apparel: an exploratory study of consumers' perception and preferences, Electron. Green. J. (2022) 1.
[180] F. Zandt, Sustainable Fashion Worldwide [cited 2024 Mrch 28]; Available from: https://www.statista.com/chart/29693/sustainable-fashion-purchasers/, 2023.
[181] S.Y. Song, Y.-K. Kim, A Human-centered approach to green apparel advertising: decision tree predictive modeling of consumer choice, Sustainability 10 (2018), https://doi.org/10.3390/su10103688.
[182] O. Rahman, et al., A study of apparel consumer behaviour in China and Taiwan, Int. J. Fash. Des. Technol. Educ. 11 (1) (2018) 22–33.
[183] O. Rahman, M. Koszewska, A study of consumer choice between sustainable and non-sustainable apparel cues in Poland, J. Fash. Mark. Manag.:. Int. J. 24 (2) (2020) 213–234.
[184] P. Gadhavi, H. Sahni, Analyzing the "mindfulness" of young Indian consumers in their fashion consumption, J. Glob. Mark. 33 (5) (2020) 417–429.
[185] D. Odiase, A Critical Examination of the Influence of Digital Culture On Fashion Consumption Amongst Young People, Manchester Metropolitan University, 2021.
[186] P.S. Norum, Examination of apparel maintenance skills and practices: implications for sustainable clothing consumption, Fam. Consum. Sci. Res. J. 42 (2) (2013) 124–137.
[187] E. Chun, et al., Business transparency and willingness to act environmentally conscious behavior: applying the sustainable fashion evaluation system "Higg Index, J. Glob. Sch. Mark. Sci. 31 (3) (2021) 437–452.
[188] J. Millward-Hopkins, P. Purnell, S. Baurley, A material flow analysis of the UK clothing economy, J. Clean. Prod 407 (2023) 137158.
[189] A. Gonçalves, C. Silva, Looking for sustainability scoring in apparel: a review on environmental footprint, social impacts and transparency, Energies 14 (11) (2021) 3032.
[190] M.P. de Brito, V. Carbone, C.M. Blanquart, Towards a sustainable fashion retail supply chain in Europe: organisation and performance, Int. J. Prod. Econ. 114 (2) (2008) 534–553.
[191] J. Wood, J. Redfern, J. Verran, Developing textile sustainability education in the curriculum: pedagogical approaches to material innovation in fashion, Int. J. Fash. Des. Technol. Educ. 16 (2) (2023) 141–151.
[192] J. West, C. Saunders, J. Willet, A bottom up approach to slowing fashion: tailored solutions for consumers, J. Clean. Prod 296 (2021) 126387.
[193] J. Xu, Y. Liu, L. Yang, A comparative study of the role of China and India in sustainable textile competition in the U.S. Market under green trade barriers, Sustainability 10 (2018), https://doi.org/10.3390/su10051348.
[194] V. Gonzalez, X. Lou, T. Chi, Evaluating environmental impact of natural and synthetic fibers: a life cycle assessment approach, Sustainability 15 (2023), https://doi.org/10.3390/su15097670.
[195] M. Finkbeiner, et al., The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044, Int. J. Life. Cycle. Assess 11 (2) (2006) 80–85.
[196] S. Ranchordás, Innovation-friendly regulation: the sunset of regulation, the sunrise of innovation, Jurimetrics 55 (2014) 201.
[197] M. Peleg Mizrachi, A. Tal, Regulation for promoting sustainable, fair and circular fashion, Sustainability 14 (2022), https://doi.org/10.3390/su14010502.
[198] S. Buchel, et al., Disrupting the status quo: a sustainability transitions analysis of the fashion system, Sustain.:. Sci. Pract. Policy 18 (1) (2022) 231–246.
[199] S. Abbate, et al., Sustainability trends and gaps in the textile, apparel and fashion industries, Environ. Dev. Sustain. 26 (2) (2024) 2837–2864.
[200] F. Beyers, J. Leventon, H. Heinrichs, Collaborative governance or state regulation? Endless efforts but little capacity for sustainability transformation of the German textile sector, Environ. Policy. Gov. 33 (1) (2023) 56–77.
[201] L. Virta, R. Räisänen, Three futures scenarios of policy instruments for sustainable textile production and consumption as portrayed in the Finnish news Media, Sustainability 13 (2021), https://doi.org/10.3390/su13020594.
[202] L.Y. Ljungberg, Materials selection and design for development of sustainable products, Mater. Des 28 (2) (2007) 466–479.
[203] Change, U.C., *Fashion industry Charter for Climate Action*. 2021, UN Climate Change, Global Climate Action.
[204] K. Baker, L.S. McNeill, A five-stage framework for sustainability certification for fashion brands: can a standardised approach work in the fashion industry? Int. J. Fash. Des. Technol. Educ. (2024) 1–15.
[205] A. Fontana, et al., Sustainability certifications and labels for the fashion industry: selection guidelines. Business Models and ICT Technologies for the Fashion Supply Chain: Proceedings of IT4Fashion 2017 and IT4Fashion 2018 7, Springer, 2019.
[206] Q. Zhang, J. Mi, H. Shen, Green labeling and sustainable development, in: W. Leal Filho (Ed.), Encyclopedia of Sustainability in Higher Education, Springer International Publishing: Cham, 2019, pp. 1–7. Editor.
[207] P. Ziyeh, M. Cinelli, A framework to navigate eco-labels in the textile and clothing industry, Sustainability 15 (19) (2023) 14170.
[208] N. Hayat, A. Hussain, H.D. Lohano, Eco-labeling and sustainability: a case of textile industry in Pakistan, J. Clean. Prod 252 (2020) 119807.
[209] A. Velasco-Molpeceres, et al., Slow fashion as a communication strategy of fashion brands on Instagram, Sustainability 15 (2023), https://doi.org/10.3390/su15010423.
[210] F. Diekel, et al., Life cycle based comparison of textile ecolabels, Sustainability 13 (2021), https://doi.org/10.3390/su13041751.
[211] S. Shim, J. Kim, Y. Na, An exploratory study on up-cycling as the sustainable clothing life at home, Fash. Text. 5 (1) (2018) 14.
[212] H. Goworek, Social and environmental sustainability in the clothing industry: a case study of a fair trade retailer, Soc. Responsib. J. 7 (2011) 74–86.
[213] S. Radhakrishnan, The sustainable apparel coalition and the higg index. Roadmap to Sustainable Textiles and clothing: Regulatory aspects and Sustainability Standards of Textiles and the Clothing Supply Chain, Springer, 2014, pp. 23–57.
[214] A. Yudina, The Higg Index: A way to Increase Sustainable Consumer Behavior, University of Colorado, 2017.
[215] S. Manshoven, W. Van, Opstal *the carrot or the stick? Stakeholder support for mandatory regulations towards a circular fashion system*, Sustainability 14 (2022), https://doi.org/10.3390/su142214671.
[216] D. Turker, C. Altuntas, Sustainable supply chain management in the fast fashion industry: an analysis of corporate reports, Eur. Manag. J. 32 (5) (2014) 837–849.
[217] R. Nayak, M. Akbari, S.M. Far, Recent sustainable trends in Vietnam's fashion supply chain, J. Clean. Prod 225 (2019) 291–303.
[218] M. Ikram, Transition toward green economy: technological Innovation's role in the fashion industry, Curr. Opin. Green. Sustain. Chem. 37 (2022) 100657.
[219] G.A.-H. Nonet, et al., Multi-stakeholder engagement for the Sustainable Development Goals: introduction to the special issue, J. Bus. Ethics 180 (4) (2022) 945–957.
[220] G. Clancy, M. Fröling, G. Peters, Ecolabels as drivers of clothing design, J. Clean. Prod 99 (2015) 345–353.
[221] D.O.C. Morais, B.S. Silvestre, Advancing social sustainability in supply chain management: lessons from multiple case studies in an emerging economy, J. Clean. Prod 199 (2018) 222–235.
[222] X. Castañer, N. Oliveira, Collaboration, coordination, and cooperation among organizations: establishing the distinctive meanings of these terms through a systematic literature review, J. Manage 46 (6) (2020) 965–1001.
[223] P. Švikruhová, V. Zabojnikova, Z. Kapsdorferova, Environmental management and its impact on CSR activities in the field of sustainable development, TalTech. J. Eur. Stud. 13 (2023) 63–86.
[224] A. Choudhary, et al., A greener world through Collaborative consumption of Apparel: an exploratory study of consumers' perception and preferences, Electron. Green. J. (2022).
[225] E. Hultberg, R. Pal, Lessons on business model scalability for circular economy in the fashion retail value chain: towards a conceptual model, ,. Sustain. Prod. Consum. 28 (2021) 686–698.
[226] L. Quijano, R. Speight, A. Payne, Future fashion, biotechnology and the living world: microbial cell factories and forming new 'oddkins', Contin. (N. Y) 35 (6) (2021) 897–913.
[227] M. Meyer, et al., Comparison of the technical performance of leather, artificial leather, and trendy alternatives, Coatings 11 (2021), https://doi.org/10.3390/coatings11020226.
[228] R. Martínez-Peláez, et al., Role of digital transformation for achieving sustainability: mediated role of stakeholders, key capabilities, and technology, Sustainability 15 (14) (2023) 11221.
[229] B. Freudenreich, S. Schaltegger, Developing sufficiency-oriented offerings for clothing users: business approaches to support consumption reduction, J. Clean. Prod 247 (2020) 119589.
[230] Wu, J. and L. Li, *Sustainability initiatives in the fashion industry*. 2019.
[231] D. Arenas, J.M. Lozano, L. Albareda, The role of NGOs in CSR: mutual perceptions among stakeholders, J. Bus. Ethics 88 (1) (2009) 175–197.
[232] F. Syrén, et al., Enhanced knittability of paper yarn from the Swedish forest by using textile finishing materials, Polym. (Basel) 13 (2021), https://doi.org/10.3390/polym13213628.
[233] H. Toker, et al., in: S.O. Idowu, et al. (Eds.), *NGOs and CSR*, in *Encyclopedia of Corporate Social Responsibility*, Berlin, Heidelberg, Springer Berlin Heidelberg, 2013, pp. 1759–1765. Editors.
[234] R. Martínez-Peláez, et al., Role of digital transformation for achieving sustainability: mediated Role of stakeholders, key capabilities, and technology, Sustainability 15 (2023), https://doi.org/10.3390/su151411221.
[235] A. MacDonald, A. Clarke, L. Huang, Multi-stakeholder partnerships for sustainability: designing decision-making processes for partnership capacity, J. Bus. Ethics 160 (2) (2019) 409–426.
[236] K.H. Bieluch, et al., Transdisciplinary research partnerships in sustainability science: an examination of stakeholder participation preferences, Sustain. Sci. 12 (1) (2017) 87–104.
[237] Filho, W. and L. Brandli, *Engaging stakeholders for sustainable development*. 2016.
[238] L. Mariani, et al., Achieving sustainable development goals through collaborative innovation: evidence from four European initiatives, J. Bus. Ethics 180 (4) (2022) 1075–1095.
[239] C. Fu, L. Lu, M. Pirabi, Advancing green finance: a review of sustainable development, Digit. Econ. Sustain. Dev. 1 (1) (2023) 20.
[240] S. Fankhauser, et al., The meaning of net zero and how to get it right, Nat. Clim. Chang 12 (1) (2022) 15–21.
[241] T. Hale, et al., Assessing the rapidly-emerging landscape of net zero targets, Clim. Policy 22 (1) (2022) 18–29.
[242] Pachauri, R.K., et al., *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. 2014: Ipcc.
[243] J. Deutch, Is net zero carbon 2050 possible? Joule 4 (11) (2020) 2237–2240.
[244] J. Rogelj, et al., Zero emission targets as long-term global goals for climate protection, Environ. Res. Lett. 10 (10) (2015) 105007.
[245] Partners, C.C., *The CarbonNeutral Protocol. The global standard for carbon neutral programmes*. 2020. p. 1–76.

[246] A. Appolloni, G. Centi, N. Yang, Promoting carbon circularity for a sustainable and resilience fashion industry, Curr. Opin. Green. Sustain. Chem. 39 (2023) 100719.
[247] J. Millward-Hopkins, P. Purnell, S. Baurley, Scenarios for reducing the environmental impacts of the UK clothing economy, J. Clean. Prod 420 (2023) 138352.
[248] C.K. Chan, J. Shin, S.X.K. Jiang, Development of tailor-shaped bacterial cellulose textile cultivation techniques for zero-waste design, Cloth. Text. Res. J. 36 (1) (2017) 33–44.
[249] N.O. Bonsu, Towards a circular and low-carbon economy: insights from the transitioning to electric vehicles and net zero economy, J. Clean. Prod 256 (2020) 120659.
[250] C. Zibunas, et al., Cost-optimal pathways towards net-zero chemicals and plastics based on a circular carbon economy, Comput. Chem. Eng 162 (2022) 107798.
[251] S. Manshoven, W. Van Opstal, The carrot or the stick? Stakeholder support for mandatory regulations towards a circular fashion system, Sustainability 14 (22) (2022) 14671.
[252] T. Nakazawa, et al., Net-zero carbon declarations by Japanese local governments: what caused the domino-like diffusion? Rev. Policy. Res. 40 (6) (2023) 853–893.
[253] A. Tleuken, et al., Legislative, institutional, industrial and governmental involvement in circular economy in central Asia: a systematic review, Sustainability 14 (13) (2022) 8064.
[254] E. D'Itria, C. Colombi, Fostering fashion ecosystems: a quadruple helix-based model for European sustainable innovation, Systems 11 (9) (2023) 478.
[255] M. Rossi, et al., Life cycle assessment of a leather shoe supply chain, Int. J. Sustain. Eng. 14 (4) (2021) 686–703.
[256] H. Zhao, H. Wang, Constructing an evaluation indicator system for sustainable fashion, in: *2021 International Conference on Diversified Education and Social Development (DESD*2021*)*, Atlantis Press, 2021.
[257] H. Wang, et al., Sustainable fashion index model and its implication, J. Bus. Res 99 (2019) 430–437.
[258] J.X. Wu, L. Li, Sustainability initiatives in the fashion industry, Fash. Ind. (2019) 1–17.