



Integrating IoT and circular economy in Textile supply chains: A closed-loop model for sustainable production using recycled PET and spent coffee grounds

Fabio De Felice^a, Mizna Rehman^a, Antonella Petrillo^{a,*}, Miguel Angel Ortiz Barrios^b, Iliaria Baffo^c

^a Department of Engineering, University of Naples "Parthenope", sola C4, Centro Direzionale Napoli, 80143, Napoli (NA), Italy

^b Department of Productivity and Innovation, Universidad de la Costa CUC, Barranquilla, Colombia

^c Department of Economics Engineering Society and Business Organization (DEIM), University of Tuscia, Largo dell'Università s.n.c., Loc. Riello, Viterbo, 01100, Italy

ARTICLE INFO

Handling Editor: Xin Tong

Keywords:

Supply chain
IoT
Waste management
VSM
LCA
SCGs
SDGs

ABSTRACT

The global textile industry is one of the most polluting and resource-intensive sectors, demanding urgent adoption of sustainable practices. To address this challenge the study proposes a closed-loop circular model for transforming textile supply chains by integrating advanced digital technologies, such as the Internet of Things (IoT), Life Cycle Assessment (LCA), and value stream mapping, with sustainable material practices. Specifically, the study explores the utilization of recycled polyethylene terephthalate (PET) and spent coffee grounds (SCG) in textile production to reduce reliance on virgin materials, decrease environmental impacts, and improve resource efficiency. A comprehensive methodological framework, including IoT-enabled real-time monitoring and LCA-based environmental assessments, was implemented in a case study conducted at a textile plant in Pakistan. Key findings include a 21.43 % reduction in lead time, a 30 % decrease in material waste, and a 25 % improvement in cycle time across production processes. Environmental benefits encompass significant reductions in carbon emissions (from 8000 to 7500 tons of CO₂), water consumption (from 12,000 to 10,000 m³), and energy use (from 55,000 to 50,000 kWh). The integration of IoT sensors, circular economy principles, and digital visualization dashboards facilitated real-time tracking and optimization of waste and resource management. These outcomes highlight the potential of this approach to promote circular economy practices and align with Sustainable Development Goals (SDGs) focused on responsible consumption, climate action, and technological innovation.

1. Introduction

The textile industry, employing 10 million workers globally (Desore and Narula, 2018; Madhav et al., 2018), produces diverse products like agrotexiles, automotive textiles, and sportswear (Roy et al., 2020). Valued at over USD 1.95 billion in 2023 (Zayed et al., 2023), the industry faces critical sustainability challenges, including high water usage i.e., over 3 trillion gallons annually and significant greenhouse gas emissions, contributing one-third of environmental chemical releases (Desore and Narula, 2018). Approximately 80 % of finished textiles are transported from developing to developed nations (Niinimäki et al., 2020). Research has addressed product design (Salo et al., 2020),

pollution management (Pattnaik et al., 2018), barriers to sustainability (Kazancoglu et al., 2020), and corporate social responsibility (Luque and Herrero-García, 2019). Recent studies highlight waste generation in fashion supply chain and propose integrated sustainability approaches (Rehman et al., 2024). Industry 4.0, circular economy principles, LCA, and IoT provide data-driven solutions, such as repurposing SCGs for fabric production (Yang et al., 2023; Ahmad et al., 2021). The textile industry consumes billions of cubic meters of water annually, with 2700 L needed per T-shirt, generates 270 kg of CO₂ emissions per person, emits 1.2 billion tons of greenhouse gases (5 % of global emissions), and produces millions of tons of textile waste. Polyester garments release 700,000 microplastic fibers, potentially contaminating the food chain (European Parliament, n.d.). Conversely, over 6 million tonnes of SCGs

* Corresponding author.

E-mail addresses: fabio.defelice@uniparthenope.it (F. De Felice), mizna.rehman001@studenti.uniparthenope.it (M. Rehman), antonella.petrillo@uniparthenope.it (A. Petrillo), mortiz1@cuc.edu.co (M.A. Ortiz Barrios), ilriaria.baffo@unitus.it (I. Baffo).

<https://doi.org/10.1016/j.jclepro.2025.145277>

Received 20 August 2024; Received in revised form 26 February 2025; Accepted 9 March 2025

Available online 11 March 2025

0959-6526/© 2025 Elsevier Ltd. All rights reserved, including those for text and data mining, AI training, and similar technologies.

Acronyms:	
AP	Acidification Potential
GWP	Global Warming Potential
IoT	Internet of Things
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
PET	Polyethylene Terephthalate
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RDP	Resource Depletion Potential
SCGs	Spent Coffee Grounds
SDGs	Sustainable Development Goals
VSM	Value Stream Mapping
R&D	Research and development
RFID	Radio Frequency Identification
RRR	Reduce, Reuse, and Recycle

Table 1
Keywords search queries utilized for literature review the Scopus database.

Keywords	Scopus Search Query	Number of articles
Textile Industry Sustainability	TITLE-ABS-KEY ("textile industry" OR "textile manufacturing" OR "textile production") AND ("sustainability" OR "sustainable practices" OR "environmental impact")	12
Supply Chain Transparency	TITLE-ABS-KEY ("supply chain transparency" OR "transparent supply chain" OR "traceability in supply chain")	7
IoT in Supply Chain	TITLE-ABS-KEY ("Internet of Things" OR "IoT") AND ("supply chain" OR "logistics" OR "manufacturing")	6
Circular Economy	TITLE-ABS-KEY ("circular economy" OR "circularity" OR "closed-loop economy") AND ("textile industry" OR "clothing industry" OR "apparel industry" OR "spent coffee grounds")	8

are discarded annually, offering significant repurposing potential and supporting recycling and reuse.

The study investigates how technologies enhance sustainability and transparency in the textile supply chain, guided by LCA analysis to assess environmental impacts (Wiedemann et al., 2022). IoT enables real-time monitoring (Manglani et al., 2019), while blockchain and RFID aid in the collection and use of SCGs (Badhwar et al., 2023; Oelze, 2017; Shen et al., 2017; Bruce et al., 2004). The study also examines the economic and environmental benefits of repurposing coffee grounds for fabric production (Gebreyessus, 2022; Panusa et al., 2013), addressing the projected increase in food waste (2.1 billion tonnes) and economic losses (\$1.5 trillion) by 2030, with a \$700 billion opportunity (Bae and Hong, 2019; Koh and Hong, 2017). Utilizing IoT secures data on resource use, reducing inefficiencies, waste, power consumption, and water impacts in the supply chain. Circular economy practices focus on reuse, recycling, and proper disposal, targeting zero waste (Uddin et al., 2023; Brun et al., 2020). The research highlights using SCGs for fabric production, integrating Industry 4.0 technologies to enhance resource efficiency, transparency, and environmental performance, offering significant economic and environmental benefits. The *research questions* addressed in this study are.

1. RQ#1. How do digital technologies improve sustainability and transparency in the textile supply chain while utilizing LCA to assess the environmental impacts of fabric production?
2. RQ#2. What strategies can be employed to optimize economic and environmental advantages of using repurposed coffee grounds for fabric production?
3. RQ#3. What obstacles and opportunities exist in implementing IoT, circular supply chain models, VSM, and LCA methodologies within the fabric supply chain, and what strategies can enhance resource efficiency and reduce waste?

This research directly aligns with SDGs 9, 11, 12, and 13 by proposing an innovative, data-driven approach that integrates IoT and LCA to enhance sustainability in the textile industry. The implementation of a closed-loop circular model addresses industry inefficiencies, promotes responsible production and consumption, reduces carbon emissions, and contributes to climate action through the development of sustainable infrastructure and practices.

The rest of the manuscript is structured as follows: Section 2 summarizes an overview on issues relating to the sustainability of the textile sector; Section 3 outlines the methodology, including IoT, circular models, and VSM; Section 4 presents the reference scenario. While Section 5 discusses the experimental scenario. Then Section 6 analyses the IoT integration and Real-Time Visualization using Node-red. Discussions are summarized in Section 7. Finally, Section 8 summarizes the main results and implications of the research.

2. Literature review: overview of digital technologies for Textile sustainability

The \$3 trillion global fashion industry contributes over 2 % to global GDP but faces challenges like waste, environmental impact, and inefficient supply chains (Shirvanimoghaddam et al., 2020; Gebhardt et al., 2021; Upadhyay et al., 2021). Textile consumption has risen to 13 kg per person annually, with two-thirds of 100 million tons of waste ending in landfills and only 15 % recycled, causing significant environmental and socio-economic problems (Shirvanimoghaddam et al., 2020).

In conducting this literature review, a comprehensive search was performed using Scopus, the largest globally recognized academic database. The search strategy utilized a combination of keywords given in Table 1.

A PRISMA flow diagram was constructed to visualize the systematic review process. Initially, **103 records** were identified through database searches and registers. After removing duplicates and excluding irrelevant records, **63 records** underwent screening. Of these, 42 reports were sought, with 40 reports ultimately assessed for eligibility. Exclusions were made based on criteria such as non-English articles, off-topic content, and unavailability of full-text. Below is a summary of the inclusion and exclusion criteria, considerations for selecting the documents to be analyzed:

Inclusion Criteria.

1. I1. Articles written in English.
2. I2. Articles that are on-topic and relevant to the scope of the review.
3. I3. Articles with full-text availability.
4. I4. Peer-reviewed journal articles.
5. I5. Articles identified through databases that fit the inclusion criteria post-screening.
6. I6. Adequate data and detail for extraction and analysis

Exclusion Criteria.

1. E1. Articles identified as duplicate records (n = 5).
2. E2. Articles marked as ineligible by automation tools (n = 10).
3. E3. Articles removed for other unspecified reasons (n = 25).
4. E4. Non-English articles (n = 2).

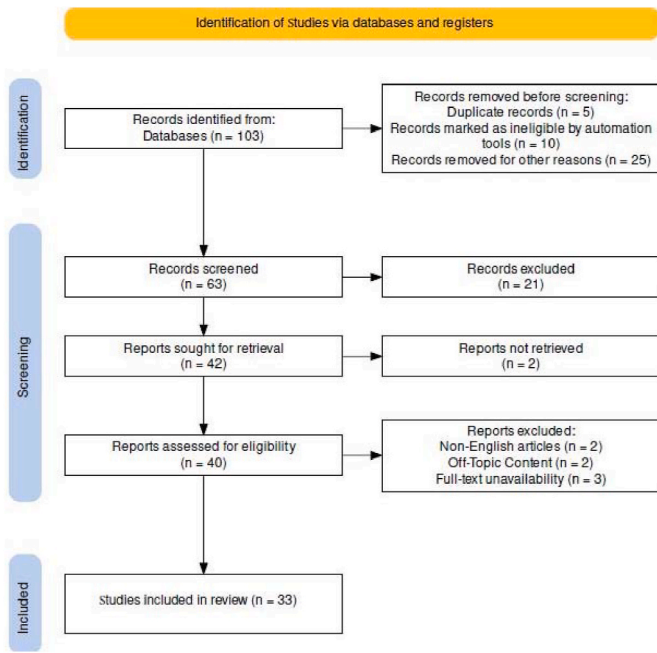


Fig. 1. PRISMA flow diagram illustrating the systematic review process.

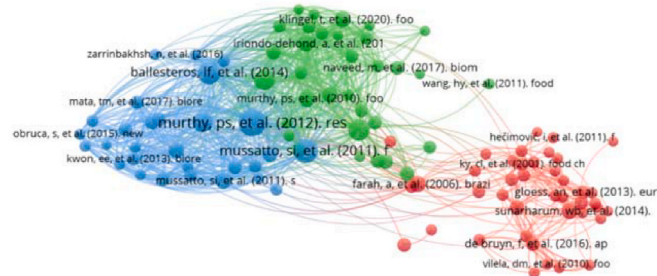


Fig. 4. VOSviewer network analysis illustrating keyword occurrences.

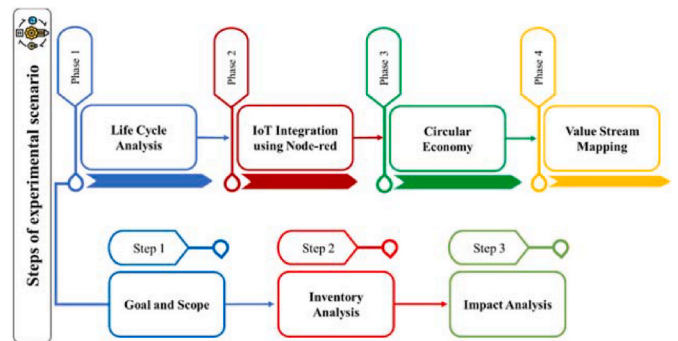


Fig. 5. Main phases of proposed methodological integrated framework (Author's elaboration).

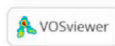


Fig. 2. Studies in textile sustainability and supply chain management (focus on SCGs utilization).

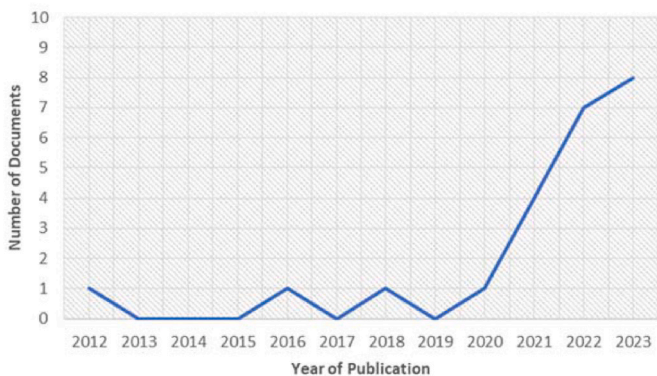


Fig. 3. Yearly distribution of documents.

- 5. E5. Off-topic articles (n = 2).
- 6. E6. Full text articles were unavailable (n = 3).

Ultimately, **33 studies** were included in the final analysis, representing the total number of studies incorporated into the literature review as shown in Fig. 1.

A citation analysis using VOS viewer was used to identify influential studies in the textile industry sustainability and supply chain management, focusing on the use of SCGs illustrated in Fig. 2. Key articles were identified based on their frequency, providing insights into the foundational research shaping current discourse.

The study analyzed publication trends over time to identify shifts and emerging topics in the field. A graphical representation of the number of articles published per year revealed notable fluctuations and areas of sustained interest in Fig. 3. The highest number of documents was 8 in 2023, followed by 7 in 2022 and 4 in 2021.

The VOSviewer network analysis revealed a variety of keywords and their associations within the field illustrated in Fig. 4 including "block-chain," "certification," "circular economy," "coffee," "supply chain," "sustainability," and "traceability". Associations with industry-specific terms like "coffee industry," "coffee supply chain," and "specialty coffee" underscored the close ties between academic discourse and practical applications.

The distribution of documents by type comprising of 70.9 %, articles, indicating a focus on detailed research findings. Conference papers contribute 11.7 %, while books chapters and reviews make up 8.7 %. In terms of the subject area, Engineering and by Materials Science have the

Table 2
Reuse of SCG and its economic and environmental impact across industries.

Waste Challenges	Innovative Solutions	Applications	Environmental Impact	Economic Impact
SCG	Composting, biofuels, brick production	Monsanto: soil enrichment BP: renewable fuel in transportation Skanska: sustainable building infrastructure	Emission reduction: 20 kg CO ₂ per kg SCG Landfill waste reduction: 30 million tons	SCG potential: 10.7 billion liters of biofuel annually Economic benefit: Estimated at \$9.5 billion
Textile Production Waste	Recycling, upcycling, circular economy models	Patagonia: upcycling textile waste for new products Owens Corning: using recycled textiles for insulation	Waste reduction: 50 % reduction in textile waste in landfills Resource conservation: Saves 1 million cubic meters of water annually	Cost savings: Estimated at \$3.2 billion through waste reduction
Food Waste	Composting, anaerobic digestion, food waste-to-energy	Whole Foods Market: composting for agriculture productivity Waste Management Inc.: food waste-to-energy conversion	30 % decrease in methane emissions Increases soil fertility by 25 %	\$5.8 billion in reduced waste disposal fees and energy generation of 50 billion kWh per year
Construction Waste	Demolition waste recycling, modular construction methods	Turner Construction Company: Modular construction methods Balfour Beatty: Sustainable construction practices Granite Construction: road construction and infrastructure development.	Material reuse: 2 million tons of building materials Reduction in Construction and demolition waste: 35–40 % of the total solid waste and 40 million tons per year landfill waste	Recycling construction waste can save up to \$4.6 billion annually
Electronic Waste (E-waste)	E-waste recycling programs, refurbishment and resale	Dell Technologies: refurbishing and reselling electronic products Best Buy: electronic waste recycling programs	Hazardous materials: Prevents 85 % from entering landfills Resource recovery: Recovers 90 % of raw materials for reuse	\$7.1 billion revenue from refurbished product sales and raw material reclamation
Chemical Waste	Closed-loop systems, chemical recycling processes	BASF: Closed-loop systems, chemical recycling processes Dow Chemical Company: Chemical production, water treatment	50 % decrease in chemical pollutants in water bodies	Efficient chemical usage saves up to \$6.3 billion annually
Plastic Packaging Waste	Biodegradable packaging, recycling initiatives	Coca-Cola: Biodegradable packaging, recycling initiatives Unilever: Food packaging, consumer goods	60 % reduction in plastic waste entering oceans Saves 2 million tons of plastic materials	Potential for brand differentiation: Increase in consumer loyalty by 25 %

Table 3
Summary of previous studies, limitations, and relevance to current research.

Study	Focus	Methodology	Key Findings	Limitations/Gaps	Relevance to Current Study
Wagner and Heinzl (2020)	Human perceptions of recycled textiles and circular fashion	Systematic Literature Review	Identified consumer understanding of sustainable products; variations in attitudes towards sustainable consumption	Limited focus on the role of IoT in enhancing consumer engagement with recycled textiles	Provides insights into consumer behavior that can inform IoT applications in promoting circular fashion
Cao et al. (2022)	Textile and product development from end-of-use cotton apparel	Experimental Study	Demonstrated the feasibility of reclaiming value from cotton waste through mechanical recycling	Downcycling issues due to fiber length reduction; lacks integration of IoT for monitoring recycling processes	Highlights the need for IoT integration to enhance recycling efficiency and product quality
Furferi et al. (2022)	Circular economy guidelines for the textile industry	Review of Existing Literature	Emphasized the necessity for industry leaders to adopt sustainable practices and tools for circular economy implementation	Does not address specific IoT technologies that could facilitate circular practices	Supports the need for integrating IoT technologies into circular economy frameworks
Zandberga et al. (2023)	Decision-making algorithm for waste recovery options	Algorithm Development	Developed criteria for evaluating textile waste recovery options, emphasizing added value and circular economy principles	Limited empirical validation of the algorithm; lacks case studies on IoT applications	Suggests a framework that can be enhanced with IoT data for better decision-making in waste recovery
Awan et al. (2021)	Industry 4.0 and the circular economy	Literature Review	Explored the intersection of Industry 4.0 technologies, including IoT, and their impact on circular economy initiatives	Primarily focused on manufacturing; limited insights into textile-specific applications	Provides a theoretical basis for integrating IoT within textile supply chains to promote circularity

highest score (20 %), followed by Environmental Science (18 %).

The literature review reveals a global perspective with contributions from researchers from various regions and continents. Regional differences in research focus reflect localized challenges and priorities in the textile industry and implementing circular economy principles. China is the leading contributor with 32 documents (16 %), followed by the United States with 30 documents (15 %). Brazil and Italy also show significant research activity with 24 (12 %) and 18 documents (9 %), respectively.

The literature highlights significant sustainability challenges in the

textile industry, including water consumption, chemical dye pollution, and poor working conditions (Sardar et al., 2022; Akter et al., 2022). Fast fashion and linear production models worsen resource depletion and waste, necessitating innovative approaches to reduce environmental impact of industry (Arrigo, 2020). Effective waste management remains a key concern for both industries, and recognizing shared challenges across markets can lead to innovative solutions, as shown in Fig. 5.

These approaches underscore the potential of SCGs to enhance textile properties and promote sustainability (Leow et al., 2021). Table 2

highlights innovative waste management strategies from various sectors (Franca and Oliveira, 2022; Hu et al., 2022; Rivera et al., 2020; Saratale et al., 2020), emphasizing the importance of using SCGs to address environmental and economic challenges.

Barriers to sustainability are also tied to dominant business models and consumer behaviours (Pedersen and Andersen, 2015). Consumer demand for ethical products has increased the need for transparency in the textile supply chain. Technologies like RFID, QR codes, blockchain, and IoT are essential for providing traceable information on product origins with secure tracking and digital credentialing systems ensuring trust and security in managing IoT device access and identity, thereby fostering consumer trust (Papasolomou et al., 2022; Carnley and Kettani, 2019; Mostafa et al., 2019; Iftekhar et al., 2021). Maouchi et al. (2018) introduced TRADE (Transparent and Decentralized), a decentralized system that enhances supply chain transparency (Mostafa et al., 2019). Smart cities further utilize IoT and blockchain to improve urban sustainability and environmental management with immutable distributed ledger and transparent transaction records (Akram et al., 2021; Iftekhar et al., 2021). Alternatively, VSM and circular supply chain models are recommended for identifying inefficiencies and promoting recycling (Loser et al., 2022; Qin and Liu, 2022; Karayilan et al., 2021). Qin and Liu (2022) introduced a scoring method to evaluate logistics models for better supply chain management, while Karayilan et al. (2021) demonstrated cross-sectoral valorisation of plastic waste to create a new biodegradable plastic product, enhancing circularity. However, existing literature often isolates these technologies, lacking a comprehensive textile sector solution. Effective implementation also requires stakeholder involvement and addressing behavioural changes as highlighted by Goodman et al. (2019). The literature review evaluates prior research on IoT integration, circular economy practices, and sustainable material use in textiles, identifying advancements and gaps providing a direct basis for the research questions. Table 3 summarizes key studies, detailing methodologies, findings, limitations, and their relevance to this research. Unlike earlier works, this study uniquely combines IoT-enabled real-time monitoring with circular economy principles, emphasizing innovative materials like SCGs and recycled PET. This approach bridges research gaps, promoting sustainable textile production by aligning digital transformation with eco-friendly materials.

While there is a substantial body of literature addressing various aspects of sustainability in textiles, there remains a notable gap in the integration of IoT technologies with circular economy practices. Existing studies often focus on theoretical approaches (e.g., Industry 4.0) or isolated material innovations (e.g., recycled cotton), overlooking IoT's potential for optimizing waste management and production processes. Limited use of IoT for real-time decision-making in waste recovery and resource efficiency underscores the need for empirical, real-world applications.

The current study aims to address this gap by exploring how IoT can be leveraged to enhance sustainability in textile supply chains, particularly through the use of recycled materials and waste management strategies.

Building upon these identified gaps the literature analysis also highlighted some important responses to the RQs, as follows.

RQ#1. How do digital technologies improve sustainability and transparency in the textile supply chain while utilizing LCA to assess the environmental impacts of fabric production?

Digital technologies enhance sustainability and transparency in the textile supply chain by enabling real-time data collection and monitoring through the IoT. These technologies facilitate better tracking of materials and processes, allowing stakeholders to understand the origins and environmental impacts of fabrics (Patti et al., 2020). LCA is employed to evaluate the environmental footprint of fabric production by analyzing every stage—from raw material extraction to disposal. By

integrating LCA with digital technologies, manufacturers can identify hotspots of resource use and emissions, make informed decisions to minimize negative impacts, and communicate sustainability efforts transparently to consumers and partners (Gharaibeh et al., 2022).

RQ#2. What strategies can be employed to optimize economic and environmental advantages of using repurposed coffee grounds for fabric production?

To optimize the economic and environmental advantages of using repurposed coffee grounds for fabric production, several strategies can be implemented. Firstly, it's crucial to invest in *material innovation* (Ahmed and MacCarthy, 2021). This involves developing methods to effectively transform coffee grounds into high-quality textile fibers, enhancing their properties to compete with conventional materials. Secondly, forming *collaborative partnerships* is essential. Collaborating with coffee producers and waste management companies can ensure a consistent supply of coffee grounds and facilitate the sharing of knowledge on recycling and repurposing this material (Ali and Haseeb, 2019). Increasing consumer awareness is another key strategy. Marketing campaigns that highlight the sustainability benefits of coffee ground fabrics can attract eco-conscious consumers and drive demand for these products (Bressanelli et al., 2021). It is also important to conduct a thorough cost analysis. This involves assessing the financial viability of incorporating coffee grounds into the production process, considering both the savings on raw materials and the potential for premium pricing on sustainable products. Finally, utilizing a LCA is crucial for continuously monitoring and improving the environmental benefits of this alternative material. This approach will ensure that the production process remains sustainable throughout the entire lifecycle of the product (Bottani et al., 2019).

RQ#3. What obstacles and opportunities exist in implementing IoT, circular supply chain models, VSM, and LCA methodologies within the fabric supply chain, and what strategies can enhance resource efficiency and reduce waste?

There are several obstacles and opportunities when it comes to integrating advanced methodologies like the IoT and circular supply chains into manufacturing processes, especially in the textile industry. One major challenge is *technical*. Implementing IoT systems often requires substantial investment in infrastructure and extensive training. This can be particularly difficult for smaller manufacturers who may not have the resources to support such investments. Another issue is *data integration*. The lack of standardized data formats and interoperability between different systems can create barriers to the smooth flow of information across the supply chain (Calheiros et al., 2023). Without effective data integration, achieving cohesive and efficient operations becomes problematic. *Cultural resistance* also plays a significant role. Shifting from traditional manufacturing practices to innovative, data-driven approaches can face pushback. Many stakeholders might be hesitant to embrace new methodologies like circular supply chains and VSM due to their established routines and skepticism about change (Ronga et al., 2020).

Despite these challenges, there are notable opportunities as well. One of the key benefits of IoT is the potential for increased efficiency. With real-time monitoring and management of resources, manufacturers can significantly enhance operational efficiency and reduce waste. There is also a growing market demand for sustainable products. As consumers become more eco-conscious, brands can differentiate themselves by adopting and showcasing environmentally friendly practices. Moreover, regulatory support is on the rise. Increasing regulations that promote sustainability in manufacturing can create a favorable environment for adopting innovative practices and technologies (Andrade et al., 2022).

To overcome the obstacles and leverage the opportunities, several strategies can be implemented. Firstly, training and education are

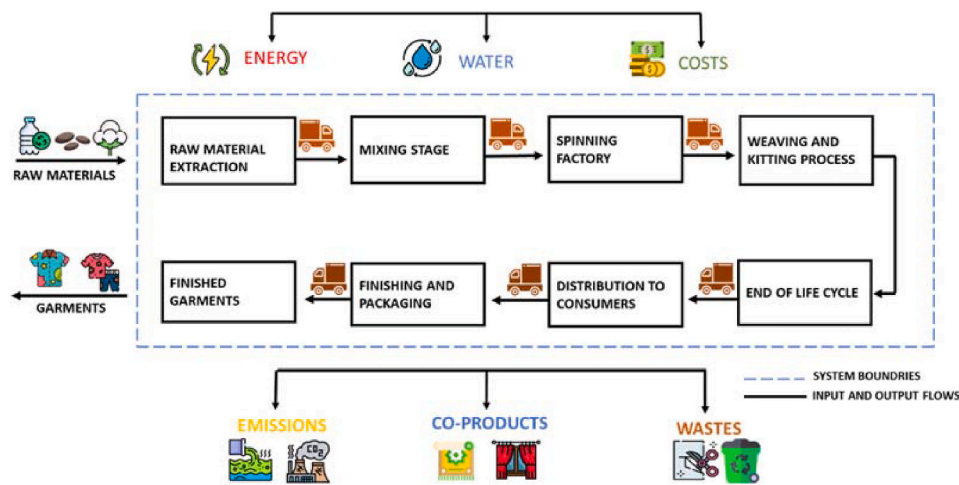


Fig. 6. System boundaries and sequential stages in the textile supply chain.

Table 4

Initial parameters for garment production and equivalent values for recycled fabric.

Parameters	Initial Values for 150 kg Garments	Equivalent for 1 kg Recycled Fabric
Waste Generation	200–300 kg	1.33–2 kg
Energy Consumption	15,000–20,000 kWh	100–133 kWh
Water Usage	50,000–75,000 L	333–500 L
Greenhouse Gas Emissions	200–300 tons CO ₂ equivalent	1.33–2 tons CO ₂ equivalent
Material Efficiency	70–80 %	90–95 %
Production Cost	\$500,000–\$750,000	\$3333–\$5000

crucial. Providing stakeholders with training on the benefits and implementation of IoT, VSM, and circular supply chains can foster a culture of sustainability and prepare them for transition. Implementing pilot projects is another effective strategy. These projects can demonstrate the effectiveness of new methodologies, allowing stakeholders to see tangible benefits and encouraging broader adoption. Collaboration is also essential. Encouraging industry players to work together can facilitate the sharing of best practices, resources, and technologies, helping to build a more robust ecosystem for sustainable fabric production. Lastly, continuous improvement is key (Manickam and Vijay, 2021). Regularly using LCA and VSM to evaluate and refine processes ensures that efforts to enhance resource efficiency and reduce waste stay aligned with overall sustainability goals.

3. Materials and methods

The project employs a multi-phase approach to evaluate and enhance environmental impacts throughout the life cycle of fabric (Fig. 5). Below is the summary of each phase.

- a. *Phase#1* involves LCA to define goals, conduct inventory analysis, and assess environmental impacts related to using coffee residue as a renewable resource (Amutha et al., 2022; Kim and Kim, 2022; Devi, 2020; Carrières et al., 2022).
- b. *Phase#2* integrates IoT with Node-Red for real-time data collection and system monitoring, enhancing operational efficiency through data-driven decision-making (Khan et al., 2022; Ahmed et al., 2021; De Vass et al., 2020).
- c. *Phase #3* adopts circular economy principles to promote reuse, recycling, and waste reduction, using circular supply chain principles (Arnold et al., 2023; Dhonde and Patel, 2020) and VSM (Hussain and

Table 5

Functions of sensors and nodes in IoT-integrated supply chain management with real-time visualization using NODE-RED.

Sensor	Purpose	Function
Waste Collection	Monitors the status of waste collection.	Triggers status updates, providing real-time insights into the efficiency and progress of waste collection operations
Transport Status	Tracks transportation phases	Captures data related to vehicle movement, route adherence, and delivery progress
Temperature & Humidity	Monitor environmental conditions during waste processing	Maintains optimal processing temperatures Ensures moisture levels within desired parameters
Water Usage	Monitors water consumption during waste processing	Triggers alerts for excess water usage, promoting sustainable practices
Power consumption	Monitors energy consumption of equipment	Tracks the energy usage of machinery and equipment to optimize efficiency and prevent wastage
Input simulation node	Simulates incoming orders or production requests	Provides a controlled environment for testing and validating the response of system to different scenarios.
Order processing node	Receives orders from the input simulation	Initiates the order fulfilment process by routing requests to relevant components.
Inventory check	Queries the inventory database	Ensures that sufficient stock is available for fulfilling the order.
Production status node	Monitors the production line	Tracks the progress of order fulfilment, including manufacturing, assembly, and packaging
Output generation node	Generates order confirmations, shipping labels, and invoices	Provides necessary documentation for customers and internal records

Figueiredo, 2023; Kumar et al., 2020) to identify and address inefficiencies.

- d. *Phase #4* focuses on optimizing the value stream by mapping processes, identifying waste, and implementing improvements.

This framework combines statistical analyses, process optimization, and customer engagement strategies to establish a benchmark for sustainability.

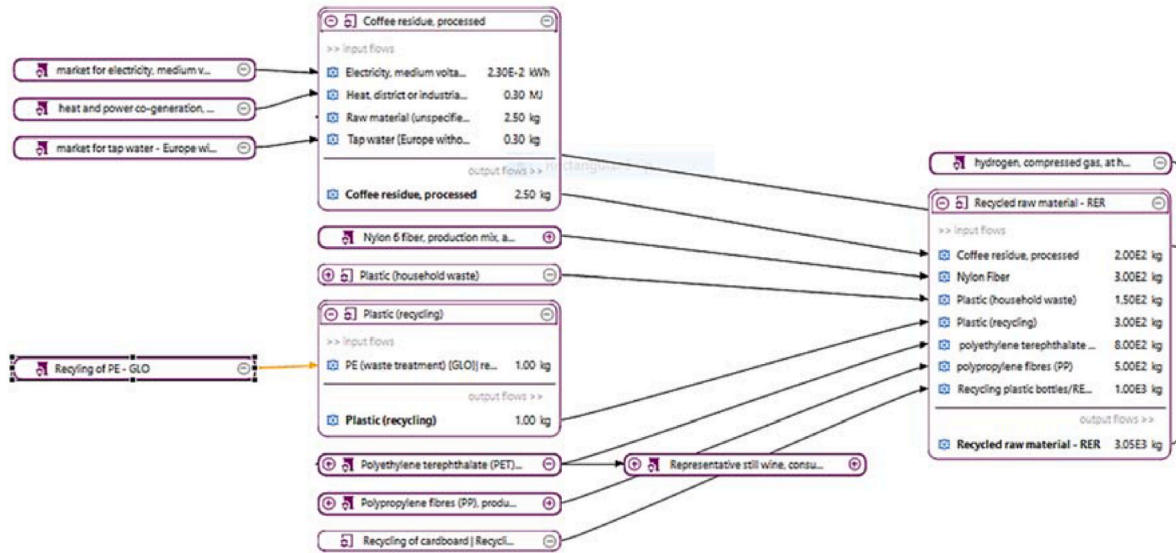


Fig. 7. Quantification of input and output flows in the initial stage of raw material extraction.

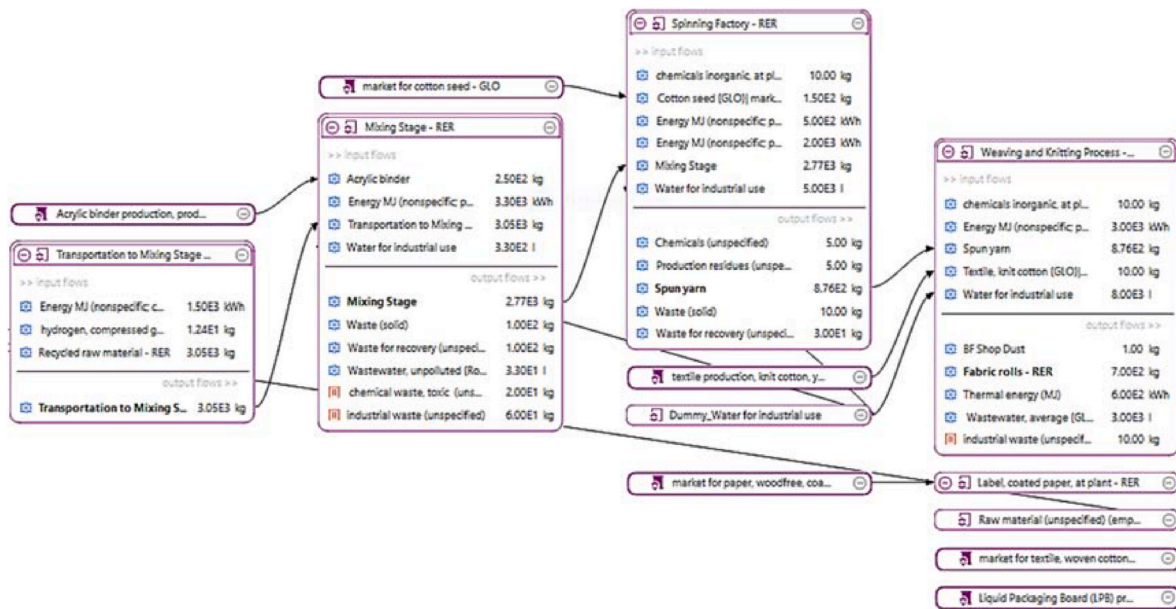


Fig. 8. Life cycle stages of transportation, mixing, spinning, weaving & knitting in open LCA.

3.1. Life cycle analysis (LCA)

3.1.1. Goal and scope

The LCA model, following a cradle-to-grave approach and adhering to ISO 14040/14044 standards, aims to evaluate the environmental impact of a textile supply chain driven by recycled materials (Jain et al., 2022). Fig. 6 depicts the system boundaries and stages, from recycled raw material extraction to end-of-life processing. Each stage, including mixing, finishing, and packaging, is analyzed for its environmental impact and resource use throughout the textile lifecycle. The functional unit is 1 kg of fabric produced from coffee residue and recycled materials (Furberg et al., 2021), allowing for performance quantification, scenario comparisons, and decision-making on resource allocation and process optimization (Petrillo et al., 2022; Tariq et al., 2021).

3.1.2. Life cycle inventory analysis

The LCI phase involved data collection and calculations to quantify

the inputs and outputs of the textile product system (Matis and Krot, 2021). Environmental flow data (e.g., energy, emissions, and resource utilization) was gathered through direct factory measurements, OpenLCA (Ecoinvent database) software simulations, peer-reviewed databases, alongside published literature and government reports for material-specific environmental factors. Inputs and outputs were carefully quantified across each process stage. This included analyzing inventory supply materials like SCGs, plastic, and recycled fibers along with transportation logistics, energy use, emissions, and waste avoidance. It assessed the transformation of coffee grounds into textile yarns (Aldabahi et al., 2021), including energy consumption, emissions from machinery, and production waste (Provin et al., 2021), optimizing dyeing methods with natural extracts (Patti and Acierno, 2022), digital printing (Rett et al., 2021), and eco-friendly dyes (Singh et al., 2021). It also emphasizes energy-efficient technologies, including waste heat recovery and solar power, and improving water recycling through closed-loop systems and advanced filtration. These strategies aim to

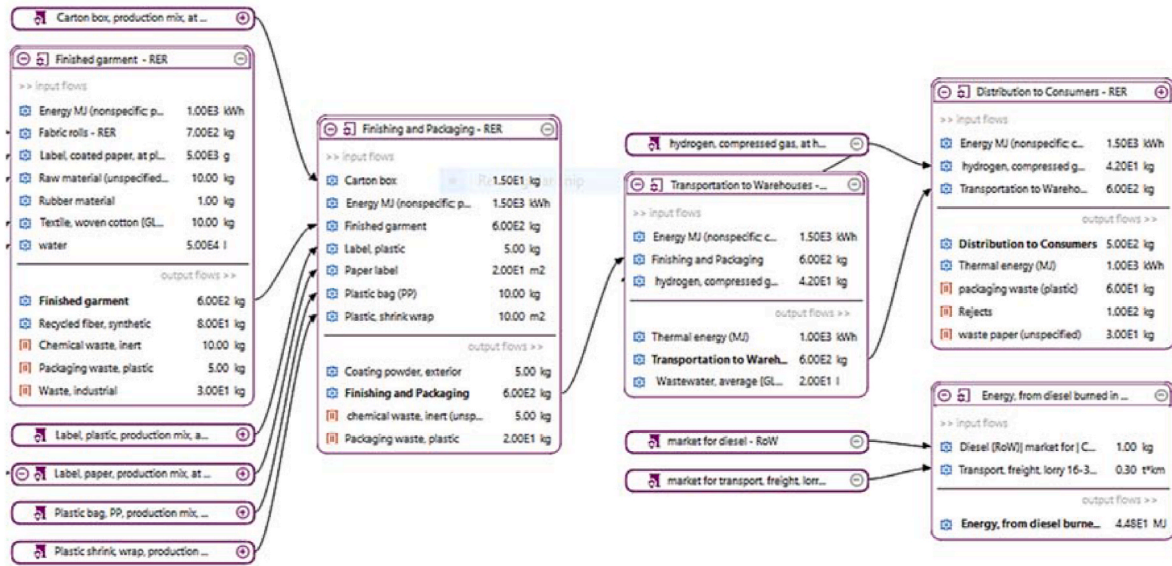


Fig. 9. LCA analysis of finishing, packaging, and distribution in Open LCA.

promote sustainability, innovation, and efficiency in the textile industry.

Before assessing the environmental impact, it is essential to calculate the inventory of environmental flows, including emissions and resource utilization. The equation for this inventory is essential for understanding the environmental footprint of system and is represented as:

$$\text{Environmental Flow} = \sum_{i=1}^n (Q_i - E_{f_i}) \quad (1)$$

Where.

- E is the total environmental flow (e.g., kg of CO₂, MJ of energy)
- Q_i is the quantity of the process input or output (e.g., kWh of electricity, kg of raw material)
- E_{f_i} is the environmental factor associated with the input or output (e.g., kg CO₂/kWh for electricity, kg CO₂/kg for material)

The GWP equation assesses the contribution of emissions to climate change by quantifying greenhouse gas emissions from various activities. It is expressed as:

$$\text{GWP} = \sum_{i=1}^n (E_i \times \text{GWP}_i) \quad (2)$$

Where.

- E_i is the emission of gas i (e.g., kg of CH₄)
- GWP_i is the global warming potential factor of gas i relative to CO₂ (e.g., CH₄ has a GWP of 28–36 over 100 years)

Understanding GWP helps prioritize mitigation strategies by identifying gases with higher warming potentials.

The AP equation quantifies the potential of emissions to cause environmental acidification, focusing on sulfur and nitrogen compounds, and is essential for assessing impacts on ecosystems and biodiversity. The equation is expressed as:

$$\text{AP} = \sum_{i=1}^n (E_i \times \text{AP}_i) \quad (3)$$

Where.

- E_i is the emission of gas i (e.g., kg of SO₂)
- AP_i is the acidification potential factor for emission i

AP aids in implementing measures to mitigate acid rain and preserve environmental quality.

The RDP equation quantifies the depletion of natural resources, such as fossil fuels and water, throughout the product lifecycle. It is vital for assessing resource scarcity and promoting sustainable resource management practices. The equation is denoted as:

$$\text{RDP} = \sum_{i=1}^n (Q_i \times \text{RDP}_i) \quad (4)$$

Where.

- Q_i is the quantity of the resource used or depleted (e.g., kg of fossil fuels, m³ of water)
- RDP_i is the resource depletion potential factor for resource i

Eutrophication potential measures the risk of nutrient pollution leading to excessive algae growth and environmental degradation.

$$\text{EP} = \sum_{i=1}^n (E_i \times \text{EPI}_i) \quad (5)$$

Where.

- E_i is the emission of nutrient i (e.g., kg of nitrogen, phosphorus)
- EPI_i is the eutrophication potential factor for nutrient i

Equation (EP), helps in understanding and mitigating nutrient pollution, guiding efforts towards sustainable nutrient management and water quality preservation.

To assess environmental and economic impacts, the following equations were used. Examining these parameters provides stakeholders with a comprehensive understanding of the environmental implications of garment production, emphasizing sustainable practices. This data serves as a foundational reference for evaluating garment production impacts and developing strategies to improve efficiency, minimize waste, and reduce environmental footprints, aligning with global sustainability goals.

Table 6
Analysis of inputs and outputs in textile supply chain for environmental impact assessment.

Stage	Inputs	Outputs
Raw Material Extraction	<ul style="list-style-type: none"> •Electricity: 2.30E2 kWh •Heat: 0.30 MJ •Raw material: 2.50 kg •Tap water: 0.30 kg •PE (waste treatment): 1.00 kg 	<ul style="list-style-type: none"> •Coffee residue, processed: 2.00E2 kg •Recycled raw material - RER
Transportation to Mixing Stage	<ul style="list-style-type: none"> •Energy MJ: 1.50E3 kWh •Hydrogen, compressed gas: 1.24E1 kg •Recycled raw material: 3.05E3 kg 	<ul style="list-style-type: none"> •Transportation to Mixing Stage: 3.05E3 kg
Mixing Stage	<ul style="list-style-type: none"> •Acrylic binder: 2.50E2 kg •Energy MJ: 3.30E3 kWh •Transportation to Mixing stage: 3.05E3 kg •Water for industrial use: 3.30E2 L 	<ul style="list-style-type: none"> •Mixing material output: 2.77E3 kg •Waste (solid): 1.00E2 kg •Waste for recovery: 3.30E1 L •Chemical waste, toxic: 2.00E1 kg •Industrial waste: 6.00E1 kg
Spinning Factory	<ul style="list-style-type: none"> •Chemicals inorganic: 10.00 kg •Cotton seed: 1.50E2 kg •Energy MJ: 5.00E2 kWh •Energy MJ: 2.00E3 kWh •Mixing material output: 2.77E3 kg •Water for industrial use: 5.00E3 L 	<ul style="list-style-type: none"> •Chemicals: 5.00 kg •Production residues: 5.00 kg •Spun yarn output: 8.76E2 kg •Waste (solid): 10.00 kg •Waste for recovery: 3.00E1 kg
Weaving and Knitting Process	<ul style="list-style-type: none"> •Chemicals inorganic: 10.00 kg •Energy MJ: 3.00E3 kWh •Spun yarn: 8.76E2 kg •Textile, knit cotton: 10.00 kg •Water for industrial use: 8.00E3 L 	<ul style="list-style-type: none"> •BF Shop Dust: 1.00 kg •Fabric rolls output: 7.00E2 kg •Thermal energy (MJ): 6.00E2 kWh •Wastewater: 3.00E3 L •Industrial waste: 10.00 kg
Finished Garment	<ul style="list-style-type: none"> •Energy MJ: 1.00E3 kWh •Fabric rolls: 7.00E2 kg •Label, coated paper: 5.00E3 g •Raw material (unspecified): 10.00 kg •Rubber material: 1.00 kg •Textile, woven cotton: 10.00 kg •Water: 5.00E4 L 	<ul style="list-style-type: none"> •Finished garment output: 6.00E2 kg •Recycled fiber: 8.00E1 kg •Chemical waste: 10.00 kg •Packaging waste, plastic: 5.00 kg •Waste, industrial: 3.00E1 kg
Finishing and Packaging	<ul style="list-style-type: none"> •Carton box: 1.50E1 kg •Energy MJ: 1.50E3 kWh •Finished garment: 6.00E2 kg •Label, plastic: 5.00 kg •Paper label: 2.00E1 m² •Plastic bag (PP): 10.00 kg •Plastic, shrink wrap: 10.00 m² 	<ul style="list-style-type: none"> •Coating powder: 5.00 kg •Finished and packed garment output: 6.00E2 kg •Chemical waste: 5.00 kg •Packaging waste, plastic: 2.00E1 kg
Distribution to Consumers	<ul style="list-style-type: none"> •Energy MJ: 1.50E3 kWh •Hydrogen gas: 4.20E1 kg •Transportation to Warehouse: 6.00E2 kg 	<ul style="list-style-type: none"> •Garments distributed output: 5.00E2 kg •Thermal energy (MJ): 1.00E3 kWh •Packaging waste (plastic): 6.00E1 kg •Rejects: 1.00E2 kg •Waste paper: 3.00E1 kg •Energy, from diesel burned: 4.48E1 MJ
Energy, from Diesel Burned	<ul style="list-style-type: none"> •Diesel: 1.00 kg •Transport, freight, lorry: 0.30 tkm 	
End-of-Life Recycling Process	<ul style="list-style-type: none"> •Chemicals: 3.00E1 kg •Rolled fabrics: 2.00E2 kg •Energy, from diesel burn: 5.00E2 kWh 	<ul style="list-style-type: none"> •End-of-life recycling: 1.50E2 kg •Label, coated paper: 1.00 kg •Plastic (recycling): 5.00 kg •Scrap: 2.00E1 kg •Solid waste: 1.00 kg •Waste for recovery: 2.00 kg

$$\text{Waste Generation} = \sum (\text{Output Waste Flows}) - \sum (\text{Input Waste Flows}) \tag{6}$$

where.

- Output Waste Flows = Total amount of waste generated at each stage of the production process.
- Input Waste Flows = Total amount of waste used or recycled at each stage of the production process.

$$\text{Greenhouse Gas Emissions} = \sum (\text{Emission Factors} \times \text{Emissions}) \tag{7}$$

Where.

- Emission Factors = Factors representing the amount of greenhouse gas emissions per unit of activity (e.g., kg CO₂ per kWh of electricity).
- Emissions = Total emissions of greenhouse gases at each stage of the production process.

$$\text{Material Efficiency} = \frac{(\text{Output Material})}{(\text{Input Material})} \times 100 \% \tag{8}$$

Where.

- Output Material = Total amount of useable material produced at each stage of the production process.
- Input Material = Total amount of raw material input at each stage of the production process.

Table 4 presents initial parameters for garment production, comparing traditional methods with the use of recycled fabric. It includes metrics on waste, energy, water usage, greenhouse gas emissions, material efficiency, and production cost.

3.1.3. Impact analysis

The study analyses the environmental impact of using coffee grounds in textiles, focusing on energy reduction, organic dyeing, and disposal methods like composting and recycling. It examines emissions, resource use, and waste, covering global warming, water use, acidification, eutrophication, human health, and toxicity. The findings highlight intervention areas for scenario analysis and strategy development.

3.2. IoT integration using node-red

This research integrates IoT technology using Node-Red to enhance textile manufacturing efficiency. Node-Red, an open-source tool, connects hardware, APIs, and services through a browser interface. The methodology involves flows for monitoring waste collection, tracking transport status, and controlling environmental factors like temperature and humidity. Sensors provide real-time data for optimal textile processing, while waste and transport data ensure efficient logistics and waste management. Water and power usage are monitored to reduce resource consumption. The integration of these IoT solutions aims to improve resource management, operational efficiency, and environmental conditions in the textile industry. Table 5 details all the used sensors and nodes in the supply chain management framework.

3.3. Closed-loop circular supply chain model for textile industry

The methodology includes a closed-loop circular supply chain model to enhance sustainability by promoting the reuse, recycling, and remanufacturing of textiles. Waste data was collected through physical audits of SCG and PET supply chains, verified by internal factory records. According to Ellen MacArthur Foundation (EMAF) circular economy principles can reduce wastes up to 80 % and greenhouse gas emissions by 44 %. In a closed loop end-of-life textiles are processed to recover

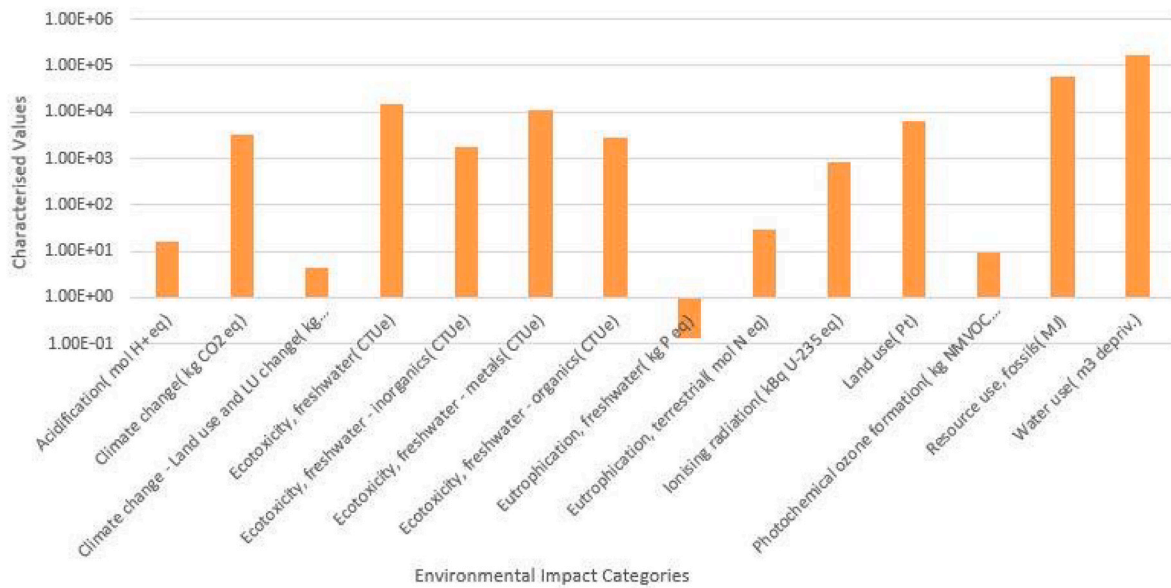


Fig. 10. Environmental impact assessment across various categories associated with the complete life cycle of garment production.

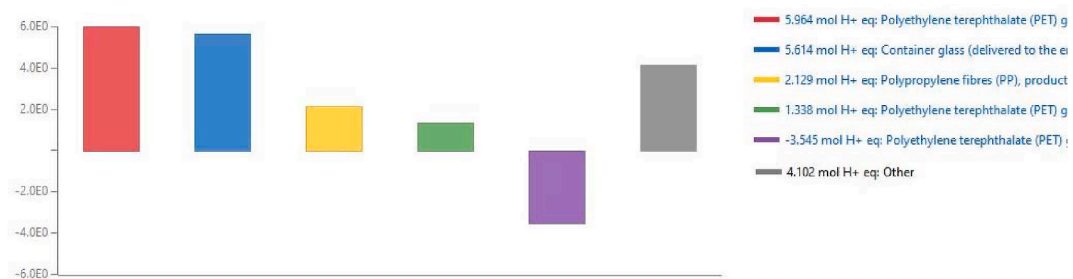


Fig. 11. Environmental impact assessment of acidification potential across all stages.



Fig. 12. Trends in Water Usage Impact assessment.

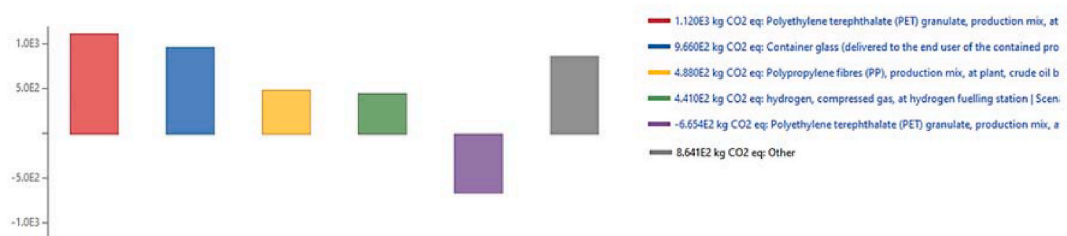


Fig. 13. Climate change impact assessment across the textile industry life cycle.

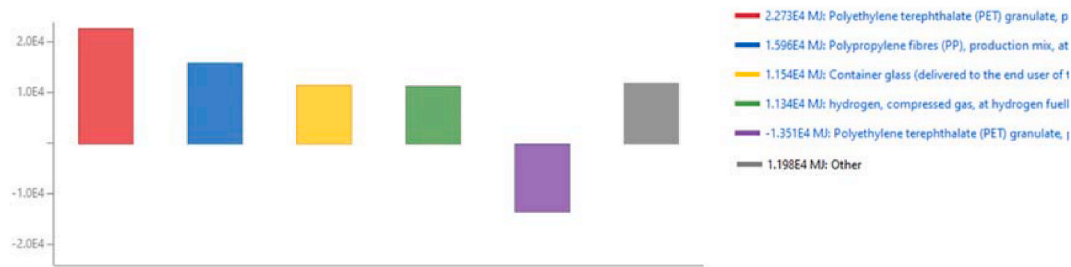


Fig. 14. Fossil resource utilization in the textile industry life cycle.

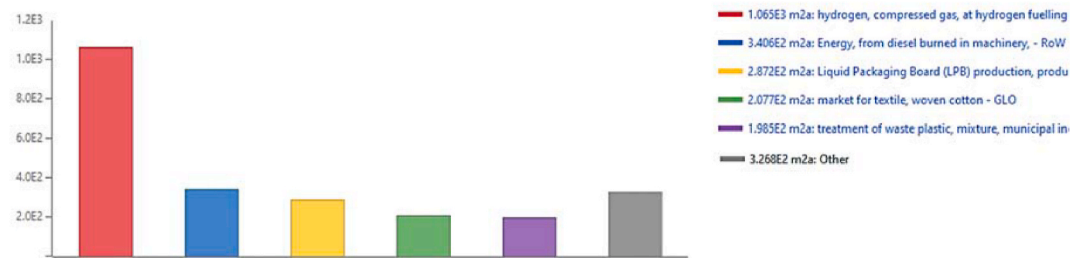


Fig. 15. Total carbon footprint assessment across garment production life cycle.

Table 7
Net cost contribution analysis for all processes in USD.

Contribution	Process	Requirement	Total Result [USD]	Direct Contribution [USD]
100.00 %	End-of-life recycling process	150.0000	1049.80579	37.73166
96.41 %	Distribution to Consumers	200.0000	1012.07413	47.05360
91.00 %	Transportation to Warehouse	240.0000	965.02053	1151.48152
	Hydrogen, compressed gas, at plant	16.8000	0.00000	0.00000
-91.00 %	Finishing and Packaging	240.0000	-186.46099	-905.55987
	Finished garment - RER	240.0000	719.09888	-76.12918
0.00 %	Label, plastic, production	21.20891	0.00000	0.00000
0.00 %	Plastic bag, PP, production	145.7194	0.00000	0.00000
0.00 %	Plastic shrink, wrap, production	4.0000	0.00000	0.00000
0.00 %	Carton box, production mix	6.0000	0.00000	0.00000
0.00 %	Label, paper, production mix	8.0000	0.00000	0.00000
0.00 %	Graphic Paper, production	12.0000	0.00000	0.00000
0.00 %	Hydrogen, compressed gas, at plant	240.0000	0.00000	0.00000
-00.00 %	Energy, from diesel burned	1800.0000	-1.68544E-13	0.00000
0.00 %	Market for diesel - RoW	40.17857	0.00000	0.00000
0.00 %	Market for transport, freight	12.05357	0.00000	0.00000

materials, which are reintegrated into production, such as chemically recycling polyester garments and when combine with plastic and SCGs, they further reduce the need for virgin materials saving significant energy. Implementing these practices could yield €22 billion in net economic benefits annually by 2030 (European Environment Agency, 2024). IoT integration with smart sensors conserves natural resources and provides economic benefits.

3.4. Value stream mapping

VSM created using Edraw Max V 10.0, was used to identify inefficiencies in the textile supply chain, as shown in Fig. 23. Data on production times, waste percentages, and material efficiency were obtained through factory logbooks and process control systems. It starts with raw material acquisition, including SCGs and PET bottles, ensuring consistent material flow and optimizing recycling. The process then includes transforming these materials into yarn (10,000 kg), fabric production through weaving or knitting, and apparel production involving bleaching, dyeing, and wet processing. Production control manages inventory and order fulfillment, while output distribution handles delivery to clients. Challenges include complex process mapping, accurate data collection, resistance to change, and cross-functional collaboration. KPIs such as first pass yield and total units produced are used to assess improvement efficacy.

$$\text{First pass yield (FYP)} = \left(\frac{\text{Good units}}{\text{Total units produced}} \right) \times 100 \quad (9)$$

Scrap calculation formula determines the amount of waste generated during production, including setup wastes, material irregularities, cutting wastes, defected fabric, and selvage scrap.

$$\text{Scrap calculation} = \text{Input inventory} \times \text{scrap rate} \quad (10)$$

Useable output reflects the quantity of acceptable products available for distribution.

$$\text{Usable output} = \text{Input inventory} - \text{scrap amount} \quad (11)$$

Uptime percentage evaluates the operational efficiency of machinery.

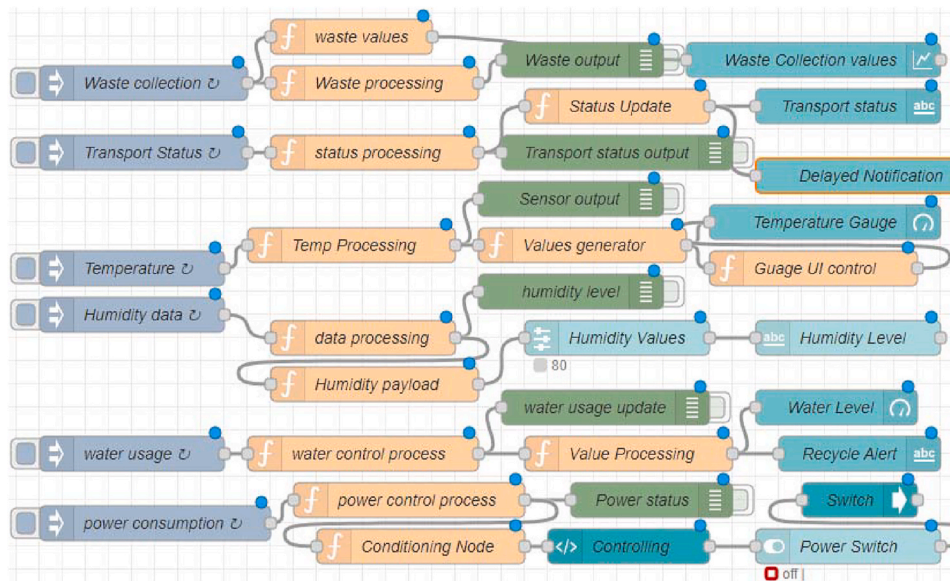


Fig. 16. Sensory integration and optimization with Node-RED software. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

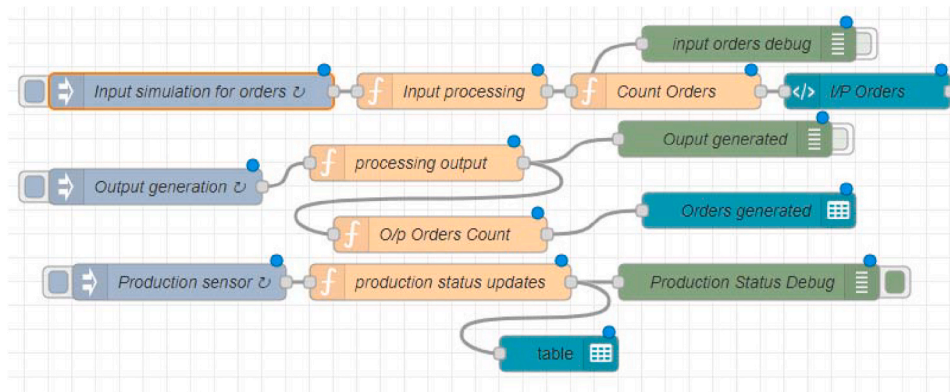


Fig. 17. Production nodes for real-time monitoring and updating.



Fig. 18. Sensor data visualization dashboard.

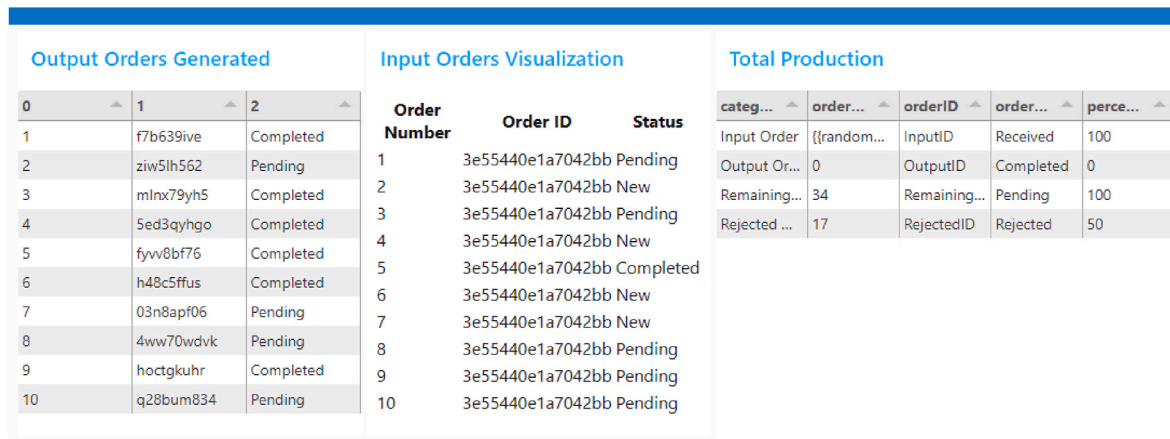


Fig. 19. Production status monitoring and visualization dashboard.

Table 8
Quantitative data and status assessment of sensors and nodes in for IoT-integrated in NODE-RED.

Sensor	Value 1	Value 2	Value 3	Value 4	Status	Min:	Max:
Waste Collection	10	7	8	10	Dispose of/Free space	0	10
Transport Status	On time	Delayed	On time	On time	On time or Contact logistics	0	1
Temperature Humidity	38 °C 47 %	40 °C 45 %	36 °C 50 %	39 °C 46 %	Normal, High or Low Within range (0 %–100 %)	0 °C 0 %	50 °C 100 %
Water Usage	89 L	92 L	87 L	90 L	In control or recycle water	0 L	150 L
Input Production Order Processing	Order ID: 3e55440e1a7042bb	Order ID: 7f65420g1c6341ab	Order ID: 2e23010f1g9040aa	Order ID: 1e91577k0b6816bc	New, Pending, Completed	N/A	N/A
Inventory Check	Order ID: mlnx79yh5	Order ID: ziw5lh562	Order ID: f7b639ive	Order ID: 5ed3qyhgo	Received, Completed, Rejected	N/A	N/A
Production Status	In stock	Out of stock	Order placed	In stock	Order inventory or material in stock	N/A	N/A
Output Generation	ID# 4ww70wdvk In process Completed	ID#03n8apf06 In process Completed	ID# h48c5ffus Completed Pending	ID# q28bum834 Completed Pending	In process or completed Completed or pending	N/A	N/A
Power	On	Off	On	Off	On/Off	50kWh	200kWh

$$Uptime (\%) = \left(\frac{Cycle\ time - Downtime}{Cycle\ time} \right) \times 100 \quad (12)$$

$$Cycle\ Time = \frac{Total\ Time}{Number\ of\ Units\ Produced} \quad (13)$$

Where.

- Cycle time signifies the duration required to complete one production cycle
- Downtime refers to periods when production is halted due to equipment malfunction or maintenance

Shortest total time determines the minimum duration required to complete a production run

$$Shortest\ total\ time = Cycle\ time + Lead\ time \quad (14)$$

Lead time denotes the duration between initiating a production order and its completion

$$Lead\ Time = Processing\ Time\ (Yarn\ Preparation) + Processing\ Time\ (Fabric\ Formation) + Processing\ Time\ (Apparel\ Production) \quad (15)$$

Finally, units per shift measures the production output achievable

within a given time frame, providing insight into workforce productivity and capacity utilization.

$$Units\ per\ shift = (Total\ shift\ time / Cycle\ time) \quad (16)$$

Available production time compares the efficiency and performance across the stages of production.

$$Available\ Time = Total\ Time - Planned\ Downtime \quad (17)$$

Value-added time is the time spent on actual processing activities which is the sum the cycle times of each stage (Yarn Preparation, Fabric Formation and Apparel Production).

$$Value - Added\ Time = C/T (1) + C/T (2) + C/T (3) \quad (18)$$

$$Process\ Cycle\ Efficiency = \left(\frac{Value\ Added\ Time}{Total\ Lead\ Time} \right) \times 100\ % \quad (19)$$

$$Takt\ Time\ (per\ batch) = \frac{Available\ Time\ (per\ day)}{Daily\ Customer\ Demand\ (in\ batches)} \quad (20)$$

These equations, applied within the textile supply chain context, enable precise quantification and analysis of production performance, facilitating continuous improvement initiatives.

Table 9

Real-Time data acquisition in IoT-enhanced textile supply chains, sensor models, data collection platforms, and operational efficiency comparison.

Stage	Sensors/Nodes Used (Model)	Software Platform	Data Collected	Baseline Scenario	Improved Scenario	Issues and Solutions
Raw Material Handling	RFID Tags (Zebra ZT410), GPS (Quectel L80)	Node-RED (MQTT Integration)	Material flow, location tracking	Manual tracking, delays (360 h)	Automated tracking, 192-h delivery (46.67 % faster)	Issue: Connectivity gaps. Solution: Use dual-mode (WiFi + LTE) GPS.
	Environmental Sensors (Bosch BME280)	Node-RED (I ² C Protocol)	Storage temperature, humidity	Limited monitoring, manual checks	Real-time environmental data with automated alerts	Issue: Sensor drift. Solution: Use temperature-compensated sensors.
	Weight Sensors (TE Connectivity FX1901)	Node-RED (Analog-to-Digital)	Load distribution, shipment weight	Manual weight check, errors	Automated weight monitoring during transportation	Issue: Sensor calibration. Solution: Regular automated recalibration.
Production Line Monitoring	Energy Meters (Schneider Electric PM5500)	Node-RED (Modbus RTU)	Power consumption, production uptime	55,000 kWh energy use	50,000 kWh (9.09 % reduction)	Issue: High cost. Solution: Prioritize critical areas for deployment.
	Vision Sensors (Omron ZFV)	Node-RED (OPC-UA)	Fabric quality, defect detection	Manual inspections, 80 % accuracy	Automated quality checks, 95 % defect detection accuracy	Issue: Legacy integration. Solution: Implement OPC-UA adapters.
	Waste Sensors (Baumer IFRM Capacitive Proximity)	Node-RED (Digital Input)	Real-time waste bin capacity	Manual waste tracking	30 % faster waste bin monitoring and response	Issue: False positives. Solution: Set material-specific detection thresholds.
Textile Processing	Power Sensors (AcuRev 1310 Modbus)	Node-RED (Modbus TCP/IP)	Machine-level energy monitoring	Manual audits, delayed response	Real-time energy tracking with 10 % consumption reduction	Issue: Sensor failures. Solution: Use redundant energy sensors.
	Humidity Sensors (Honeywell HIH-6130)	Node-RED, Siemens MindSphere	Environmental monitoring during processing	Inconsistent monitoring	Predictive maintenance with 25 % improved uptime	Issue: Sensor reliability. Solution: Use industrial-grade models.
	Ultrasonic Flow Sensors (Siemens SITRANS FS230)	Node-RED (Modbus RTU)	Water consumption during dyeing/washing	12,000 m ³ (excessive consumption)	10,000 m ³ (16.67 % reduction)	Issue: Maintenance costs. Solution: Regular calibration schedules.
Logistics & Distribution	GPS Modules (Quectel L80), Weight Sensors (TE Connectivity FX1901)	AWS IoT Core (MQTT)	Vehicle routes, load distribution	Inefficient route optimization	Dynamic optimization with 21.43 % lead-time reduction	Issue: Routing inefficiencies. Solution: Integrate real-time traffic data.
Order Processing Nodes	Input Simulation Node (Virtual IoT Device)	Node-RED (Custom API)	Simulates incoming orders	Manual simulation, inconsistent scenarios	Automated input processing with 30 % faster execution	Issue: Data mismatch. Solution: Implement controlled test cases.
	Order Processing Node (Virtual IoT Device)	Node-RED (API Integration)	Automates order handling and tracking	Manual handling, delays	20 % faster order fulfillment with automated monitoring	Issue: Process bottlenecks. Solution: Optimize routing logic.
Inventory Management	Inventory Check Node (Simulated Inventory System)	Node-RED (Database Query)	Monitors real-time stock availability	Manual inventory tracking, 24-h delay	Automated stock monitoring with instant alerts	Issue: Data lag. Solution: Use real-time database queries.
Production Status	Production Status Node (Virtual IoT Device)	Node-RED (Custom API)	Monitors production status in real-time	Manual periodic checks, 60-h cycle time	Automated monitoring, reducing cycle time by 20 %	Issue: Limited tracking. Solution: Enable continuous status tracking.
Data Management & Reporting	Cloud Storage (AWS IoT Core), Apache Kafka	Node-RED (Stream Processing)	Consolidated sensor data for analytics	75 % data utilization, manual review	80 % automated data analytics and real-time alerts	Issue: Security concerns. Solution: Implement encrypted data transfer.
	Output Generation Node (Custom Report Generator)	Node-RED (API Output)	Generates reports and alerts	Delayed report generation	25 % faster report generation with automated documentation	Issue: Information overload. Solution: Use stakeholder-specific dashboards.

4. A pilot case study: reference scenario

The integration of SCG into the textile industry and circular economy offers sustainable solutions. With 60 million tons of SCG waste generated annually from 3.5 billion daily cups of coffee, SCG can be repurposed for composting, biofuels, and bricks, reducing emissions and waste (Saberian et al., 2021). SCG carbonized at 160 °C produces yarn more efficiently than traditional 600 °C methods TextileMates (2019). It also aids natural textile dyeing, with methanol as an effective solvent (Agrawal and Chopra, 2020; Haji and Naebe, 2020; Haji and Rahimi, 2020; Kiran et al., 2020). Combining SCG with recycled polyester creates green fiber yarn, matching the performance of virgin materials. Annually, 9.3 million tons of coffee generate 6 million tons of SCG waste (McKenna, 2018; ICO, 2017), highlighting significant potential for sustainable repurposing. Studies confirm the potential of SCGs to improve textile dyeability and color fastness. when combined with mordants (Mongkhlorattanasit et al., 2021; Nam and Xiang, 2019; Hong, 2018; Y. Lee, 2006). Both industries require robust tracking systems to meet

increasing consumer demand for sustainability criteria.

The Pakistani textile industry, a key driver of the national economy, contributes about 8.5 % to GDP and employs 40 % of the industrial workforce (Tasneem and Khan, 2024). In fiscal year 2021–2022, textile exports reached \$15.4 billion, up from \$13.8 billion the previous year, though they later declined to \$16.7 billion in FY24 from \$19.3 billion in FY22 (APTMA, 2024). As the fourth-largest cotton producer in the world, Pakistan is known for its quality yarn, fabric, and garments (S. Khan et al., 2023). The industry, comprising segments like spinning, weaving, and garment manufacturing, had 1221 ginning units, 442 spinning units, capacity of 13.3 million spindles and 200,000 rotors for yarn production and 10,000 looms as of 2021 (APTMA, 2021). Modernization efforts include eco-friendly dyes and water-saving technologies (Wahab and Hussain, 2020). Challenges such as energy shortages, fluctuating cotton prices, and competition persist, but the Textile Policy 2020–2025 aims to boost exports to \$25 billion by 2025, highlighting its importance to the economic future of Pakistan (Ministry of Commerce, 2022).

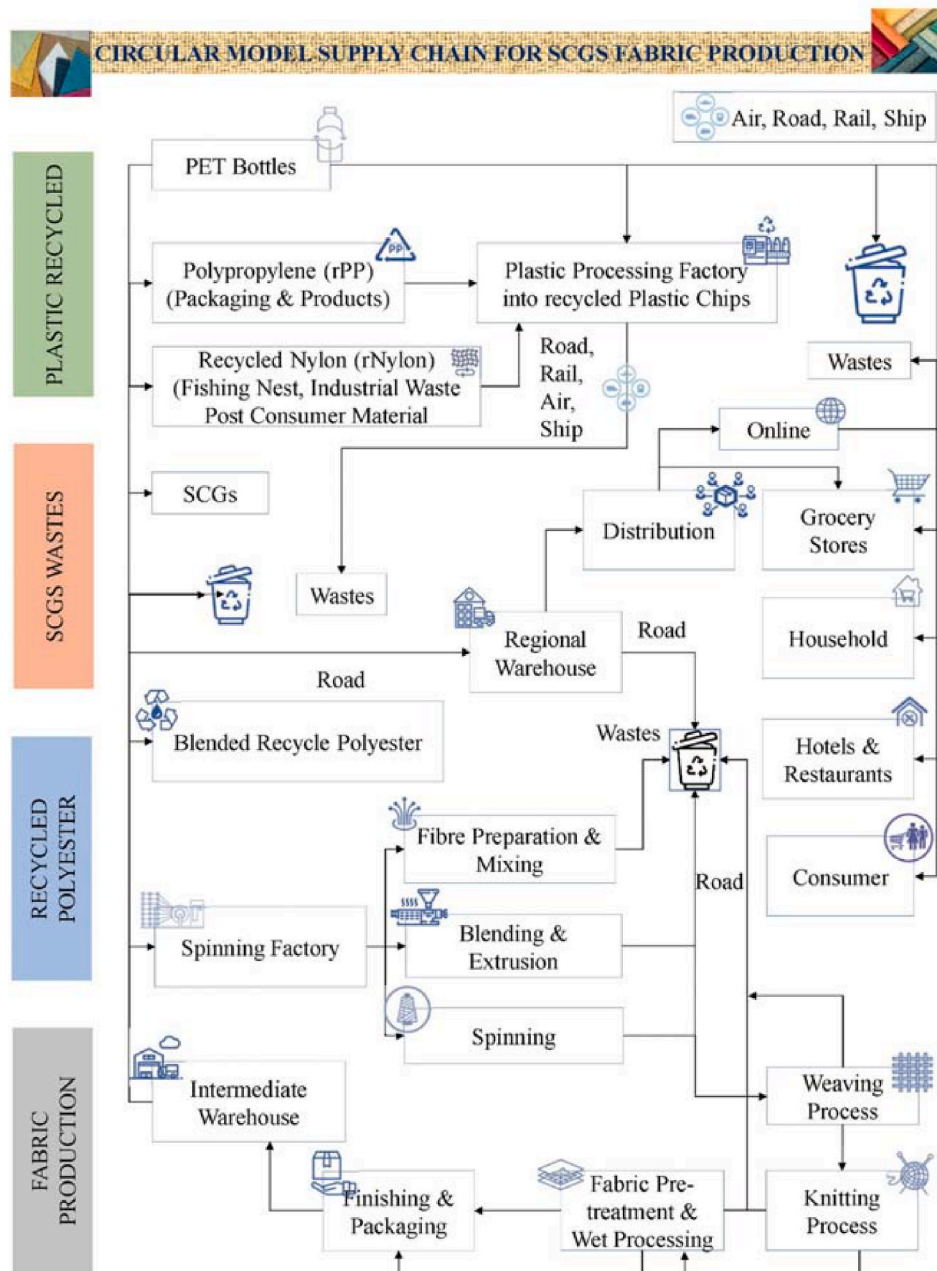


Fig. 20. Closed-loop circular supply chain model maximizing sustainability through continuous resource circulation.

Given the critical role of Pakistani textile sector and its modernization efforts, studying this industry is strategically important. Integrating SCG-derived materials into the textile supply chain supports these initiatives and addresses current challenges (Leow et al., 2021).

The following sections discuss the findings from each phase of study, highlighting how this approach can tackle industry challenges and serve as a model for circular economy principles and digital technologies in other sectors and regions. Data reliability was ensured through cross-verification with factory records and third-party audits.

5. Life cycle analysis: experimental scenario

5.1. Stage 1: raw material extraction

During the raw material extraction stage in the LCA analysis using OpenLCA 2.0, various input and output flows are quantified to assess

environmental impact as shown in Fig. 7. Inputs include $2.30E-2$ kWh of electricity, 0.30 MJ of heat, 2.50 kg of raw material, and 0.30 kg of tap water. Outputs consist of processed coffee residue, nylon 6 fiber, and recycled plastics, with $3.05E3$ kg of recycled raw material produced. This quantification offers a detailed view of resource use and waste generation, setting the stage for further LCA analysis.

5.2. Stage 2: LCA assessment of industrial processing in textile production

In the LCA phase covering transportation, mixing, spinning, and weaving/knitting stages, input and output flows are analyzed to assess environmental impacts illustrated in Fig. 8. Transportation of raw cotton from Punjab and Sindh to textile mills uses $1.50E3$ kWh of energy and $1.24E1$ kg of compressed hydrogen gas. The mixing stage inputs include $3.05E3$ kg of recycled raw material, $2.50E2$ kg of acrylic binder, $3.30E3$ kWh of energy, and $3.30E21$ units of water, producing 2.7763 kg of yarn

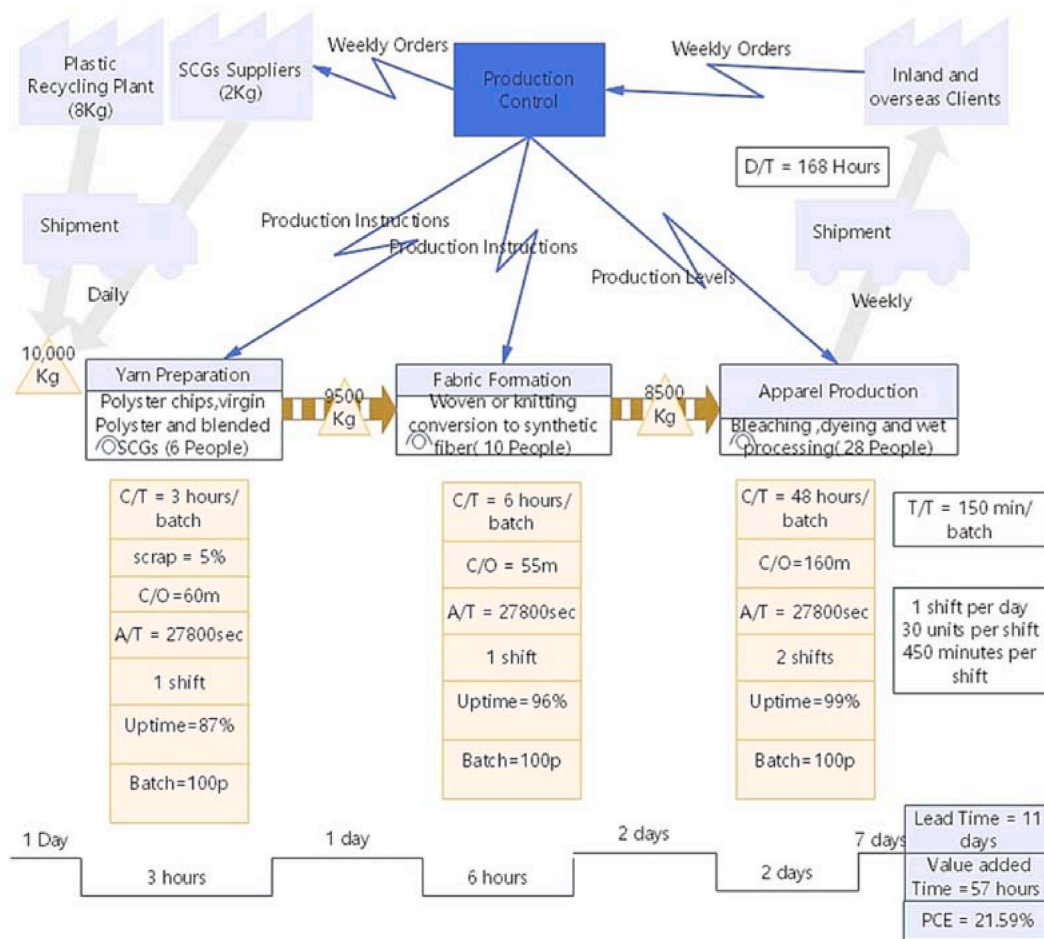


Fig. 21. Fabric production VSM.

input material, 1.00E2 kg of solid waste, and 2.00E1 kg of toxic chemical waste. The spinning stage uses 10.00 kg of inorganic chemicals, 1.50E2 kg of cottonseed, 7.00E2 kWh of energy and 2.77E3 kg of mixed materials, outputting 8.76E2 kg of spun yarn and 10.00 kg of solid waste. Finally, the weaving/knitting stage inputs 3.00E3 kWh of energy, 8.76E2 kg of yarn, and 8.00E3 units of water, yielding 7.00E2 kg of fabric rolls, 6.00E2 kWh of thermal energy, and 10.00 kg of industrial waste and materials related to paper labels and liquid packaging boards. This analysis details resource use and waste generation across the textile production process.

5.3. Stage 3: LCA analysis of finishing, packaging, and distribution stage

In the finished garment manufacturing process, 1.00E3 kWh of energy is used to produce 7.00E2 kg of fabric rolls, coated and labelled with 5.00E3 grams of raw materials, including 1.00 kg of rubber. The finishing stage consumes 10.00 kg of woven cotton textile and 5.00E4 L of water, yielding 6.00E2 kg of finished garments, 8.00E1 kg of recycled fibers, 10.00 kg of chemical waste, 5.00 kg of plastic packaging waste, and 3.00E1 kg of industrial waste.

Next stages include packing and transportation. Packing uses 1.50E3 kWh of energy, 15 kg of carton boxes, 5 kg of plastic labels, 20 m² of paper labels, 10 kg of plastic bags, and 10 m² of plastic shrink wraps. The output includes 600 kg of finished garments, 5 kg of chemical waste, and 20 kg of plastic waste. For transportation to warehouses, 1.50E3 kWh of energy, 42 kg of hydrogen gas, and 600 kg of garments are used, with outputs of 1.00E3 kWh of thermal energy, 20 L of wastewater, 60 kg of packaging waste, wastepaper (30 kg) and 100 kg of rejects. These processes ensure efficient garment production, packaging, and distribution

while minimizing environmental impacts. These comprehensive steps contribute to the efficient distribution and storage of the manufactured garments while minimizing environmental impacts depicted of each step in Fig. 9.

5.4. Stage 4: end-of-life recycling process

In the final stage of the garment life cycle, materials are disposed of and recycled to minimize waste and maximize resource recovery, supporting a circular economy. Inputs to this process include 30 kg of chemicals, 200 kg of rolled fabrics, and 500 kWh of energy from diesel. Energy derived from diesel burning powers the recycling machinery. Outputs include 150 kg of recycled materials, 1 kg of coated paper labels, 5 kg of recycled plastic, 20 kg of scrap, 1 kg of solid waste, and 2 kg of materials for recovery. This stage ensures responsible management of materials at the end of their life cycle. Detailed input and output resources are listed in Table 6.

5.5. Impact assessment

Table A.1 in the Appendix details the comprehensive environmental impact assessment of the textile supply chain, focusing on impact category EF3.0. Tables A.2 and A.3 in Appendix provide weighted and normalized results, highlighting the significance of each impact category. The four impact categories selected “climate change (SDG 13: Climate Action), water consumption (SDG 6: Clean Water and Sanitation), fossil resource consumption (SDG 7: Affordable and Clean Energy), and acidification potential (SDG 12: Responsible Consumption and Production)” were chosen not solely on the basis of their numerical scores but because

Table 10
Comparative analysis of initial and final VSM Metrics.

Metric	Initially applied VSM	Final designed VSM	Improvement Description
Lead Time	14 days	11 days	Reduced by 3 days (21.43 %)
Material Waste	18.5 Kg	12.775 Kg	Reduced by 30 %
Process Efficiency	60 %	75 % of initial	Improved by 25 %
Scrap (Yarn Preparation)	6.25 %	5 %	Reduced by 20 %
Cycle Time (Yarn Prep)	3.75 h/batch	3 h/batch	Reduced by 25 %
Cycle Time (Fabric Form)	7.5 h/batch	6 h/batch	Reduced by 25 %
Cycle Time (Apparel Prod)	60 h/batch	48 h/batch	Reduced by 25 %
Changeover Time (Yarn Prep)	75 min	60 min	Reduced by 25 %
Changeover Time (Fabric)	68.75 min	55 min	Reduced by 25 %
Changeover Time (Apparel)	200 min	160 min	Reduced by 25 %
Available Time (Yarn Prep)	20850 s	27800 s	Increased by 25 %
Available Time (Fabric)	20850 s	27800 s	Increased by 25 %
Available Time (Apparel)	20850 s	27800 s	Increased by 25 %
Uptime (Yarn Prep)	69.6 %	87 %	Improved by 25 %
Uptime (Fabric)	76.8 %	96 %	Improved by 25 %
Uptime (Apparel)	79.2 %	99 %	Improved by 25 %
Takt Time (per unit)	2 min/unit	1.5 min/unit	Improved due to overall efficiency gains
Takt Time (per batch)	200 min/batch	150 min/batch	Improved due to overall efficiency gains
Total Lead Time	14 days (336 h)	11 days (264 h)	Reduced by 3 days (72 h), 21.43 % reduction
Delivery Time	360 h (15 days)	168 h (7 days)	Delivery time reduced by 192 h
Process Cycle Efficiency	17 %	21.59 %	Significant improvement due to reduced lead time and increased efficiency

Table 11
Textile industry sustainability metrics and benchmarks.

Indicator	Description	Initial Value	Final Value	Industry Benchmark	Industry Standard
Carbon Footprint	Total amount of greenhouse gas emissions produced by the textile supply chain	8000 tons CO ₂	7500 tons CO ₂	9000 tons CO ₂	8500 tons CO ₂
Water Consumption	Total volume of water used in textile production processes	12,000 m ³	10,000 m ³	15,000 m ³	13,500 m ³
Energy Consumption	Total energy consumed during textile manufacturing processes	55,000 kWh	50,000 kWh	60,000 kWh	57,000 kWh
Waste Generation	Total amount of waste generated by textile production	250 tons	200 tons	300 tons	280 tons
Waste Reduction Progress	Percentage reduction in waste generated compared to previous reporting period	10 %	15 %	8 %	12 %
Circular Economy Adoption (LCA) Score	Percentage of materials sourced from circular supply chain models	30 %	40 %	25 %	35 %
IoT Data Utilization	Overall environmental impact score of textile products, based on LCA	80/100	85/100	75/100	78/100
Node-RED Integration Efficiency	Percentage of IoT data effectively used in monitoring and improving sustainability practices	75 %	80 %	70 %	72 %
VSM, Lead Time	Efficiency rating of Node-RED integration in optimizing waste management systems and resource utilization	4/5	4.5/5	3.5/5	4/5
Cycle Time (Yarn Preparation)	Total time from <order to delivery	14 days	11 days	12 days	10 days
Cycle Time (Fabric Formation)	Time taken to prepare yarn per batch	3.75 h/batch	3 h/batch	3.5 h/batch	3 h/batch
Cycle Time (Apparel Production)	Time taken to form fabric per batch	7.5 h/batch	6 h/batch	7 h/batch	6 h/batch
	Time taken to produce apparel per batch	60 h/batch	48 h/batch	55 h/batch	50 h/batch

they are most representative of the environmental challenges intrinsic to textile production. These indicators are particularly sensitive to changes induced by our IoT-enabled circular economy model, capturing critical aspects such as high energy demand, significant water usage, reliance on fossil fuels, and the environmental effects of chemical processes. Moreover, these categories align with international sustainability standards and the SDGs targeted by this research, thereby providing a robust framework for assessing the environmental benefits of our proposed approach.

Fig. 10 reveals key environmental impacts, with 3213.29 kg CO₂ eq., from climate change, 171445.37 m³ water use, and 60046.04 MJ fossil resource consumption as major contributors. Acidification (15.60 mol H⁺) and freshwater ecotoxicity (10869.42 CTUe) also pose significant impacts, while eutrophication (0.13 kg P equivalent) and ionising radiation (800.65 kBq U-235 equivalent) are lower. This emphasizes the need to address water use, emissions, and resource consumption to mitigate environmental impacts effectively.

Fig. 11 shows that PET granulate contributes the most to acidification, with 5.964 mol H⁺ eq (red bar). Container glass follows with 5.614 mol H⁺ eq (blue bar), and Polypropylene fibers (PP) contribute 2.129 mol H⁺ eq (yellow bar). Interestingly, recycled PET production

Table 12
Cost-Benefit analysis of IoT and circular economy practices.

Category	IoT and Circular Economy	Conventional Processes	Net Savings/Benefits
Implementation Cost	\$50,000 (sensors, software, training)	\$10,000 (basic equipment upgrades)	-\$40,000 (Higher initial cost)
Operational Cost (Annual)	\$15,000 (maintenance and data storage)	\$20,000 (manual oversight, inefficiencies)	+\$5000 (Lower annual costs)
Resource Efficiency Savings	\$30,000 (reduced water and energy use)	\$5000 (minimal efficiency gains)	+\$25,000
Waste Reduction Savings	\$20,000 (30 % reduction in waste)	\$5000 (conventional disposal methods)	+\$15,000
Revenue from Lead Time Gains	\$25,000 (faster order fulfillment)	\$0 (no efficiency improvement)	+\$25,000
Environmental Compliance	\$10,000 (reduced fines, eco-branding)	\$0	+\$10,000
Net Annual Benefit	\$65,000	\$15,000	+\$50,000

Table 13
Strategic solutions proposed for textile industry challenges by this study.

Aspects	Challenges	Solutions posed by SCGs	Obstacles in Technologies	Opportunities in Technologies
Chemical utilization and environmental contamination	Chemicals in dyeing, finishing, and treating textiles poses substantial environmental and health risks	Coffee grounds replace synthetic chemicals, mitigating pollution through natural dyeing processes.	High research costs for optimizing natural dyeing processes	Reduced environmental impact and improved worker health
Supply chain fragmentation and complexity	Fragmented supply chain, with multiple tiers across globe hinders transparency and traceability.	Circular models with recycled materials streamline sourcing, aided by IoT (for real-time tracking and monitoring) and VSM mapping to optimize processes.	Stakeholder resistance and training needs for adopting IoT and VSM techniques	Efficient supply chains
Fast fashion and over-consumption	Fast fashion leads to overconsumption and frequent disposal of clothing items.	Coffee-derived materials encourage durable, high-quality garments encouraging circularity.	Cultural shifts and consumer education for sustainable fashion	Innovative business models like rental and resale platforms
Carbon footprints and energy use	Energy-intensive operations in Textile production contribute to carbon emissions.	Coffee grounds offset emissions, requiring less energy for extraction and processing, as demonstrated by LCA analysis.	Initial investment and operational changes for energy-efficient technologies	Cost savings, environmental benefits, competitive advantages
Inadequate consumer awareness	Lack of awareness hampers demand for sustainable products	Coffee-ground integration educates and fosters eco-consciousness.	Overcoming consumer inertia requires targeted marketing and education	Increased demand for sustainable products among consumers and industry innovation

Table 14
Process integration, purpose alignment, and industry impacts within the closed-loop circular supply chain model.

Process	Steps	Purpose	Industry Implications
Input collection junctures	<ul style="list-style-type: none"> Collection of SCGs from coffee shops and cafes. Gathering of plastic waste (PET bottles) from various sources. 	<ul style="list-style-type: none"> Establishes the initial point of material flow. Ensures a steady supply of raw materials 	<ul style="list-style-type: none"> Efficient waste collection logistics. Reduction of landfill waste. Resource availability for recycling.
Waste flow management design	<ul style="list-style-type: none"> Integration of best practices from literature. Designing efficient waste flow pathways. Identifying critical junctures for waste handling. 	<ul style="list-style-type: none"> Streamlines material movement. Minimizes bottlenecks. Enhances resource utilization. 	<ul style="list-style-type: none"> Improved operational efficiency. Reduced waste handling costs. Enhanced sustainability.
Waste characterization and volume assessment	<ul style="list-style-type: none"> Analyzing the composition of SCGs, plastics, and fabrics. Quantifying waste volumes. 	<ul style="list-style-type: none"> Understand material properties. Determine recycling feasibility. 	<ul style="list-style-type: none"> Informed decision-making. Targeted recycling efforts. Resource optimization.
Recycling Facilities	<ul style="list-style-type: none"> PET bottles processed into recycled plastic chips. SCGs collected and transported to regional warehouses. Blended recycled polyester produced from SCGs. 	<ul style="list-style-type: none"> Transform waste into useable materials. Close the loop in the circular model. 	<ul style="list-style-type: none"> Reduced virgin material usage. Lower environmental impact. Creation of sustainable products.
Intermediate Warehouses	<ul style="list-style-type: none"> Blending & extrusion of recycled materials. Spinning and weaving processes. Fabric pre-treatment & wet processing. Finishing & packaging. 	<ul style="list-style-type: none"> Prepare recycled fabrics for distribution Ensure quality and consistency. 	<ul style="list-style-type: none"> High-quality recycled textiles. Market-ready products. Circular economy promotion.
Distribution to Consumer Points	<ul style="list-style-type: none"> Finished products distributed to grocery stores, households, hotels, and restaurants. 	<ul style="list-style-type: none"> Reach end consumers Close the consumption loop. 	<ul style="list-style-type: none"> Circular product lifecycle. Consumer awareness of sustainability. Market demand for eco-friendly goods.
Consumer Waste Collection	<ul style="list-style-type: none"> Waste generated at consumer points (e.g., used textiles). Collected for recycling. 	<ul style="list-style-type: none"> Restart the circular model. Prevent waste leakage. 	<ul style="list-style-type: none"> Continuous material flow. Extended product life cycles. Reduced landfill burden.

has a negative impact, reducing acidification by $-3.545 \text{ mol H}^+ \text{ eq}$ (purple bar), indicating an environmental benefit in terms of AP.

Fig. 12 illustrates that hydrogen production significantly impacts water resources, with $251,800 \text{ m}^3$ of water deprivation. Cotton seeds also contribute $19,104.7 \text{ m}^3$. The purple bar indicates hydrogen fuelling for transportation, which consumes just $5.579\text{E-}5 \text{ m}^3$, reflecting a minimal environmental impact.

The data depicted in Fig. 13 illustrates the environmental impact of various materials on climate change, measured in $\text{kg CO}_2 \text{ equivalent}$. PET granulate has a significant contribution of $1.120 \text{ E}3 \text{ kg CO}_2 \text{ eq}$. Hydrogen fuel impacts vary, contributing $4.410\text{E}2 \text{ kg CO}_2 \text{ eq}$. However, recycled PET granulate shows a negative impact, reducing emissions by $-6.6542\text{E}2 \text{ kg CO}_2 \text{ eq}$, highlighting its role in mitigating climate change.

The bar chart pertaining to resource use in Fig. 14 highlights fossil resource consumption across materials. PET used in bottles and packaging consumes $2.2730 \text{ E}+4 \text{ MJ}$ (red bar). PP fibers in textiles account for $1.5960 \text{ E}+4 \text{ MJ}$ (blue bar). Hydrogen production and distribution

require $1.1340\text{E}+4 \text{ MJ}$ (green bar). Whereas, recycled PET reduces fossil energy use by $-1.3510\text{E}+4 \text{ MJ}$ (purple bar). Recycled PET reduces energy consumption, conserving fossil fuels and reducing greenhouse gas emissions. It optimizes resource use, transforming waste into new products. The energy savings from recycled PET exceed its production costs, leading to net fossil fuel conservation and supports environmental sustainability.

The bar chart in Fig. 15 highlights the environmental impact of various categories, measured in total CO_2 . The red bar represents hydrogen as compressed gas at fueling stations, showing the highest impact at $10.653 \text{ m}^2\cdot\text{a}$, primarily due to CO_2 emissions from production and transportation. Diesel combustion in machinery follows with $3.40622 \text{ m}^2\cdot\text{a}$, contributing significantly to air pollution and climate change. The treatment of waste plastic has the lowest impact at $1.9852 \text{ m}^2\cdot\text{a}$, though it still releases CO_2 , emphasizing the need for more sustainable practices like reduction, reuse, and recycling.

Table 7 shows the unit cost implications of each process. End-of-life

Table 15
Socio, ethical, environmental impacts of using SCGs in textile production and its impacts beyond textiles.

Social Implications	Ethical Implications	Environmental Implications	Impact Beyond Textiles
Generates jobs in waste management and fabric production.	Ensures fair compensation for farmers and workers.	Reduces waste sent to landfills, aiding conservation efforts.	Inspires sustainability initiatives in various industries. Nespresso recycles coffee capsules into new products.
Provides training and skill development for workers, enhancing employability.	Promotes transparency and ethical business practices.	Lowers demand for virgin resources, like water and energy.	Drives innovation in waste management, such as the use of coffee waste in construction by Kafa Biosphere
Fosters community engagement in sustainability efforts.	Addresses concerns about resource exploitation.	Reduces the carbon footprint of textile manufacturing	Spurs demand for sustainable products. Starbucks upcycles coffee grounds for agricultural and energy uses.
Raises awareness of recycling and waste reduction.	Meets consumer preferences for eco-friendly products.	Minimizes water pollution and soil contamination.	Creates opportunities for entrepreneurship. Bio-bean converts coffee waste into biofuels.
Empowers communities to tackle environmental challenges.	Mitigates risks of inequality and unethical practices.	Promotes reuse of waste materials in textile production.	Fosters cross-sector partnerships. Rapanui integrates recycled coffee grounds into clothing lines.
Empowers marginalized communities.	Upholds environmental justice principles.	Preserves biodiversity and ecosystems.	Sustainable fashion brands, including Patagonia, H&M Conscious, Eileen Fisher, Adidas Parley, and Stella McCartney, shape consumer preferences and market trends.

6. IoT integration and Real-Time Visualization using node-red

Utilizing Node-RED flows, data collection and visualization have been optimized for real-time insights into waste collection, transportation, and processing (Fig. 16). This approach enhances decision-making and productivity (Babu et al., 2023; Gunasekaran et al., 2023; Fatima et al., 2022; Haricha et al., 2021). Node-RED enables seamless sensor communication, real-time data processing, and visualization of key metrics (Osaretin et al., 2020; Simpkin et al., 2020). IoT sensors provide visibility into asset movement (Cil et al., 2021; Gbadamosi et al., 2021), leveraging GPS for tracking shipments and packages (Balfaqih et al., 2023; Tyagi et al., 2022) and gathering critical data on conditions, location, and movement (Abel et al., 2021; Sharma et al., 2020), similar to SenseAware system of FedEx (FedEx | System Down). Moreover, IoT integration supports predictive maintenance to ensure optimal equipment performance and preventing potential breakdowns (Hafeez et al., 2021).

Fig. 17 provides the production and order processing system, detailing the role of each node within the workflow. Quality control nodes inspect inventory and finish products to meet standards before shipment. Output nodes connect to packaging for labeling and protection. Real-time tracking integrates GPS and RFID for logistics coordination, enabling customers to track orders. Feedback nodes collect customer insights, and automated alerts notify teams of issues like low inventory or delays. ERP Integration Nodes can be extended to ensure continuous data flow between production, inventory, and finance systems (Barna et al., 2021; Zdravković et al., 2021). The Order completion node marks the end of the processing cycle, highlighting the efficiency of system in managing order fulfillment.

Fig. 18 illustrates the benefits of integrating IoT technologies in supply chain management, highlighting real-time monitoring, waste management, and environmental control. IoT tracking devices in transport vehicles enable real-time route monitoring, immediate status updates, reducing delivery delays, and saving costs (supporting SDG 9). IoT waste meters alert for timely bin emptying, enhancing waste management and compliance with regulations (aligning with Ecological Standards for Waste Management and SDG 11). Humidity and temperature sensors in production facilities ensure optimal conditions, maintaining material quality and compliance with quality standards (contributing to SDG 12 and ISO 14001). Additionally, IoT sensors monitor and regulate power consumption, promoting sustainable energy use.

Incorporating IoT devices into manufacturing equipment enables real-time tracking of machine performance, material usage, and production speed, ensuring compliance with ISO 9001 and SDG 9. Data is centralized for instant reports on production efficiency, supporting ISO 14001 and SDG 12. Node-RED enhances data visualization using live dashboard (Fig. 19), aiding quick decision-making and compliance with Ecological Standards for Manufacturing and SDG 11.

Table 8 presents the numerical values of sensors and nodes in the IoT-integrated supply chain management framework indicating their status at different time intervals. The status column indicates if values are within the target range or requires attention. The minimum and maximum columns define the acceptable range for each parameter.

To provide a detailed view of IoT integration across the textile supply chain, Table 9 summarizes the types of sensors, software platforms, and data management methods employed at each stage, along with the key challenges faced and corresponding solutions.

The proposed IoT-enabled and circular economy model is highly scalable, utilizing platforms like Node-RED and AWS IoT Core, and sensors such as Schneider Electric PM5500 and Bosch BME280, adaptable to small, medium, and large textile operations. Circular economy practices, including recycled PET and SCG integration, can be scaled incrementally, with flexible solutions for different regions. Pilot studies demonstrate a 21.43 % reduction in lead time and 30 % waste reduction, confirming the model's scalability and cost-effectiveness across varying

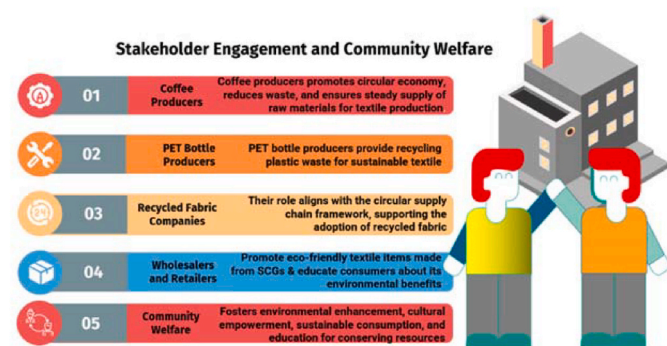


Fig. 22. Stakeholder engagement for collaborative efforts and community impact for sustainable textile production.

recycling costs \$1049.81 per unit, while efficient distribution channels cost \$1012.07 per unit. Hydrogen gas transportation to the warehouse costs \$1151.48 per unit but does not add to overall expenses. Finishing and packaging, using recycled materials, save \$186.46 per unit, reflecting a 15.55 % cost reduction. Some processes have no direct impact on costs. Understanding these cost dynamics helps in optimizing resource allocation and operational decisions to enhance financial outcomes.



Fig. 23. Exploring avenues for future research in sustainable textile production.

operational scales and locations.

6.1. Circular supply chain model

This study developed an optimized circular supply chain model for the spent coffee ground and textile supply chain using Wondershare Edraw Max 10.0. The model emphasizes waste minimization, resource optimization, and recovery. It focuses on collection points in coffee shops, cafes, waste collection entities, and recycling facilities for managing SCGs, plastics, and recycled fabrics given in Fig. 20. It encourages thorough product separation and efficient storage methods to maintain product quality. The design promotes the principles of RRR and incorporates eco-conscious transportation strategies to reduce carbon footprint and costs. This involves tactics like load consolidation and favoring eco-friendly vehicle choices wherever feasible. Collaboration with local businesses and stakeholders is key to channeling materials back into reuse. Through waste flow management design, Waste Characterization and Volume Assessment gauge the magnitude of the circular model and identify potential avenues for waste utilization.

6.2. Value stream mapping

The designed VSM reveals significant improvements in the production process, including a 30 % reduction in lead times (from 14 days to 11 days), a 20 % decrease in material waste, and a 25 % increase in process efficiency as shown in Fig. 21 and the comparative analysis between the initial and final VSMs are detailed in Table 10. The methodology integrates statistical analysis, process optimization, and customer engagement to tackle supply chain challenges and enhance sustainability in the fabric industry. By addressing non-value activities such as excessive transportation delays, inefficient packaging, and redundant inventory, significant improvements were achieved. For example, optimizing transportation reduced lead times by 21.43 %, while streamlining yarn preparation cut cycle times by 25 %, from 3.75 h to 3 h per batch. These changes resulted in a 15 % overall reduction in cycle times, boosting process efficiency and sustainability.

6.3. Interpretation using sustainability reports

The framework integrates data from IoT devices, circular supply chain models, waste management systems, and LCA to produce comprehensive sustainability reports. These reports detail key indicators such as carbon footprint, water consumption, and energy usage. They highlight high water usage processes and promote energy-efficient technologies. Circular models and waste data set waste reduction

targets. Data visualization tools convert complex data into accessible graphs, aiding in the assessment of environmental performance. This approach helps the textile industry generate robust sustainability reports, guiding strategic decision-making. Table 11 shows initial and final values of key sustainability indicators alongside industry benchmarks and standards.

6.4. Mechanical performance evaluation of recycled PET and SCG vs. conventional fabrics

Mechanical properties (tensile strength, abrasion resistance, flexural rigidity, elongation at break) were tested on fabrics made from recycled PET and SCG blends, compared to virgin polyester. ASTM and ISO standards were followed for testing.

- **Tensile Strength:** Fabrics made from recycled PET and SCG showed a 7 % decrease in tensile strength (mean strength: 300 MPa) compared to virgin polyester (mean strength: 320 MPa), which is within acceptable limits for non-load-bearing textiles.
- **Abrasion Resistance:** No significant difference in abrasion resistance, with both materials achieving >15,000 cycles on the Martindale test, suitable for everyday applications.
- **Flexural Rigidity:** Recycled fabrics showed a 5 % increase in flexural rigidity (mean: 15.2 N mm) compared to virgin polyester (mean: 14.5 N mm), beneficial for stiffer applications like outerwear.
- **Elongation at Break:** A 12 % decrease in elongation (recycled: 22 %, virgin: 25 %) indicates slightly lower flexibility, which may limit use in high-stretch applications like sportswear.

While mechanical performance is slightly lower in recycled fabrics, the environmental benefits, such as 30 % reduction in material waste and 25 % lower carbon footprint, make these materials viable for a wide range of applications, particularly non-load-bearing textiles, confirming their suitability for sustainable production.

7. Discussion

The present research addresses these gaps by introducing an integrated approach combining sustainability with IoT to optimize resource use and waste management. The study contradicts previous research by F. Jia et al. (2020), Wynn and Jones (2022), and Sahu et al. (2021), indicating potential circular economy adoption but not fully exploring its integration with digital technologies like IoT. Also, the study achieved a 30 % reduction in material waste and a 25 % improvement in process efficiency, outpacing the 15 % waste reduction noted by

Moosavi et al. (2021). Despite challenges in IoT scalability (Magrini et al., 2021; Liu and Mishra, 2022), the research demonstrated a 25 % uptime increase and a 21.59 % improvement in process cycle efficiency, with a 21.43 % reduction in lead time, effectively addressing both environmental and operational inefficiencies consistent with Gharaibeh et al. (2022), highlighting real-time data's role in optimizing production cycles. Environmental impact reductions were significant, with a 7 % decrease in carbon footprint and a 16.67 % reduction in water consumption, supporting Wiedemann et al. (2022) on the environmental benefits of recycled materials. The EF3.0 assessment confirmed improvements in ecotoxicity and eutrophication, aligning with Bressanelli et al. (2021) on the positive impact of sustainable materials like recycled PET and SCG. Furthermore, the study incorporated SCG and recycled PET into the textile supply chain, improving textile properties as seen in Leow et al. (2021) and Moosavi et al. (2021). These results align with sustainability goals of industry leaders like Inditex (Zara) and H&M, who could adopt IoT-enabled systems to further reduce inefficiencies, minimize downtime, and achieve cost savings. For example, the findings support H&M's target to use 100 % sustainable materials by 2030 by demonstrating how recycled PET and SCG can reduce material costs and environmental impacts. The research also highlights the scalability of its IoT and circular economy model for diverse applications. Large enterprises like Adidas and Nike can integrate IoT systems at scale for global supply chain optimization, while small and medium-sized enterprises (SMEs) can implement modular IoT solutions to improve resource tracking and reduce waste incrementally, allowing them to compete in eco-conscious markets. For practical validation, global textile companies such as Inditex (Zara) and H&M have implemented IoT-based tracking for supply chain optimization, but our study extends this approach by integrating IoT with a closed-loop circular economy model (Li et al., 2024; López et al., 2021). The demonstrated reductions in waste (30 %) and energy consumption (9 %) are aligned with sustainability strategies adopted by firms such as Patagonia, North face and Adidas, who are investing in textile recycling and smart manufacturing (Rahaman and Khan, 2024). By incorporating real-time resource monitoring, this model provides an operational roadmap for industries aiming to meet circular economy and sustainability targets.

Furthermore, incorporating organic and industrial waste materials, such as rice husk, cotton stalks, spent distillery grains, and wood pulp, into textiles presents additional opportunities to enhance sustainability. For example, blending these cellulose-rich materials with recycled PET reduces reliance on virgin fibers, decreases landfill waste. Studies show cotton stalks' potential for bio-geopolymer composites, aligning with sustainable textile goals (Zhou et al., 2020). Co-pyrolysis of cotton stalks with other materials enhances reactivity and generates useful by-products, supporting energy generation (Ding et al., 2023). Spent distillery grains improve functional properties through bioprocessing (Schettino et al., 2021), and integrating them into biogas production reduces environmental pollution (Duguma, 2024). Rice husk, rich in silica, and wood pulp waste for lyocell fiber production further contribute to sustainable textiles (Keshav et al., 2021). The adoption of these practices supports a circular economy while improving cost efficiency.

A cost-benefit analysis comparing IoT and circular economy practices with conventional processes highlights the economic viability of adopting sustainable technologies. Although IoT implementation incurs higher initial costs, annual savings through resource efficiency, waste reduction, and lead time improvements significantly offset these investments. Table 12 details the monetary impacts across key categories, demonstrating a net annual benefit of \$50,000, thereby supporting the financial sustainability of these practices.

The cost-benefit analysis was conducted using Microsoft Excel for financial modelling and OpenLCA for environmental impact assessments. The research presents a data-driven methodology that fills gaps in previous studies, setting a new standard for sustainability and digital practices in the textile industry. It offers a replicable industrial model.

The proposed digital transformation, using coffee grounds in fabric production and circular supply chains, targets waste reduction. Table 13 highlights how these solutions address industry challenges. By integrating VSM and IoT, inefficiencies are identified and improved, while coffee ground-derived materials enhance sustainability and promote responsible consumer behaviour.

Recycling PET, particularly in textiles, can release microplastics during manufacturing and washing, threatening aquatic ecosystems and biodiversity. Solutions include using microfiber filters in washing machines, closed-loop recycling systems to minimize fiber shedding, and developing biodegradable fibers to reduce microplastic release. Recycling PET is energy-intensive, contributing to carbon emissions if powered by non-renewable sources. To address this, renewable energy should power recycling facilities, and energy-efficient technologies and methods should be implemented like mechanical recycling (using low-energy machinery), enzymatic recycling (using enzymes to break down PET), and solvent-based recycling (using solvents at lower temperatures). Additional concerns include chemical use and wastewater generation; solutions include adopting green chemistry for non-toxic chemicals and advanced wastewater treatment to remove contaminants. This strategy integrates sustainability, technology, and consumer education, promoting an eco-friendly future for the textile industry besides other creative and cultural sectors. Table 14 details the processes, steps, and industry implications within the circular supply chain, highlighting operational and environmental benefits.

The discussion explores the implications and future directions of the study, highlighting benefits like waste reduction, carbon emission mitigation, and efficient resource use. The approach inspires other industries such as packaging (Gebhardt et al., 2021; Wang et al., 2020), electronics (Magrini et al., 2021), construction (Benachio et al., 2020), cultural and creative (Mercan et al., 2020; Car et al., 2019), food (Pakseresh et al., 2022; Sun and Wang, 2022) and agriculture (Esposito et al., 2020) to adopt circular economy principles and digital transformations, aligning with SDGs (12,9,13 and 17). However, challenges include data precision issues (Zubaydi et al., 2023), influenced by sensor calibration and environmental circumstances, affordability for smaller operations (Kumar and Chopra, 2022), resistance to behavioral changes (Rejeb et al., 2022), effective marketing and awareness (Jia et al., 2023) and scalability and compatibility concerns (Mirani et al., 2022). Overcoming these requires cross-sector collaboration and tailored strategies. Despite these challenges, the project sets a path toward sustainable progress, emphasizing the need for ongoing research and adaptability.

Table 15 details the implications of using spent SCGs in textile production.

Fig. 22 shows key stakeholders, coffee producers, PET bottle makers, recycled fabric firms, wholesalers, retailers, and community groups working together to drive sustainability in the textile industry through circular economy principles.

Fig. 23 highlights future research areas in sustainable textile production, like nanotechnology and 3D printing (Rivera et al., 2023), consumer behavior towards eco-friendly products (Kumar et al., 2022; Sinha et al., 2022), supply chain integration, and economic viability. It guides researchers and industry stakeholders to focus on these areas for advancing sustainability, stressing the need for interdisciplinary collaboration.

8. Conclusion

In conclusion, this paper highlights the importance of sustainable practices in transforming the textile industry, emphasizing waste reduction, process optimization, and conscious consumption. The coffee and textile industry case study illustrates broader applicability to sectors with similar supply chain and environmental challenges. The coffee industry exemplifies progress through its use of IoT and blockchain, creating a model for improving traceability, sustainability, and efficiency in textiles. This approach reduces environmental impact and sets

a model for broad sustainability efforts, benefiting both the textile sector and other industries like cultural and creative sectors.

This research highlights its effectiveness through IoT integration, circular supply chains, waste management, and LCA, producing detailed sustainability reports. These reports reveal a reduction in carbon emissions from 8000 to 7500 tons CO₂, water use from 12,000 to 10,000 m³, and energy consumption from 55,000 to 50,000 kWh. Waste generation decreased from 250 to 200 tons, with circular economy adoption rising from 30 % to 40 %. Data visualization tools enhance accessibility, aiding stakeholders in managing environmental performance.

While this research presents significant progress but faces limitations including data availability, precision, and affordability. Behavioral changes in consumers and industries also meet resistance, requiring effective marketing and collaboration with creative sectors for success. This research suggests future investigation avenues such as emerging technologies, consumer behavior towards sustainable textiles, and supply chain collaboration for economic viability. Future research should specifically explore the integration of Digital Twin technology with LCA methodologies to enhance real-time impact assessment. Moreover, extending IoT-enabled circular models to other industrial sectors such as construction materials or biopolymer-based textiles to further validate the approach. Investigating the economic feasibility of predictive maintenance within smart textile factories and service-oriented models, such as Textile-as-a-Service (TaaS), will provide deeper insights into sustainability-driven business transformations. Addressing its limitations and leveraging strengths, it paves the way for a sustainable and competitive textile industry, contributing to global SDGs like responsible consumption (SDG12), innovation (SDG9), climate protection

(SDG13), and partnerships (SDG17).

CRediT authorship contribution statement

Fabio De Felice: Writing – original draft, Supervision, Methodology, Conceptualization. **Mizna Rehman:** Writing – original draft, Methodology, Data curation, Conceptualization. **Antonella Petrillo:** Writing – original draft, Methodology, Data curation, Conceptualization. **Miguel Angel Ortiz Barrios:** Writing – original draft, Validation, Data curation, Conceptualization. **Ilaria Baffo:** Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

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

Acknowledgement

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on February 2, 2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU – Project Title PRISMA Platform (Physical internet Regenerative Sustainable MAterials) – CUP I53D23001660006 - Grant Assignment Decree No. 961 adopted on 30/June/2023 by the Italian Ministry of Ministry of University and Research (MUR).

Appendix A

Table A1
Impact Assessment Results for Textile Industry Supply Chain - Impact Category EF3.0

Name	Category	Impact assessment result	Unit
Acidification	EF 3.0 Method	15.60210372	mol H+ eq
Climate change	EF 3.0 Method	3213.287615	kg CO ₂ eq
Climate change - Biogenic	EF 3.0 Method	0.678749288	kg CO ₂ eq
Climate change - Fossil	EF 3.0 Method	3208.183413	kg CO ₂ eq
Climate change - Land use and LU change	EF 3.0 Method	4.425453083	kg CO ₂ eq
Ecotoxicity, freshwater	EF 3.0 Method	15337.91883	CTUe
Ecotoxicity, freshwater - inorganics	EF 3.0 Method	1809.129878	CTUe
Ecotoxicity, freshwater - metals	EF 3.0 Method	10869.42071	CTUe
Ecotoxicity, freshwater - organics	EF 3.0 Method	2844.111199	CTUe
Eutrophication, freshwater	EF 3.0 Method	0.132487151	kg P eq
Eutrophication, marine	EF 3.0 Method	2.65076136	kg N eq
Eutrophication, terrestrial	EF 3.0 Method	28.8577908	mol N eq
Human toxicity, cancer	EF 3.0 Method	1.28E-06	CTUh
Human toxicity, cancer - metals	EF 3.0 Method	1.07E-06	CTUh
Human toxicity, cancer - organics	EF 3.0 Method	2.05E-07	CTUh
Human toxicity, non-cancer	EF 3.0 Method	3.49E-05	CTUh
Human toxicity, non-cancer - inorganics	EF 3.0 Method	1.44E-06	CTUh
Human toxicity, non-cancer - metals	EF 3.0 Method	3.24E-05	CTUh
Human toxicity, non-cancer - organics	EF 3.0 Method	9.81E-07	CTUh
Ionising radiation	EF 3.0 Method	800.6451099	kBq U-235 eq
Land use	EF 3.0 Method	6465.123176	Pt
Ozone depletion	EF 3.0 Method	4.78E-04	kg CFC11 eq
Particulate matter	EF 3.0 Method	1.34E-04	disease inc.
Photochemical ozone formation	EF 3.0 Method	9.169447098	kg NMVOC eq
Resource use, fossils	EF 3.0 Method	60046.03724	MJ
Resource use, minerals and metals	EF 3.0 Method	0.001987515	kg Sb eq
Water use	EF 3.0 Method	171445.3744	m ³ depriv.

Table A2

Weighted environmental impact assessment across various categories in Pt units

Impact category	Weighted results in Pt
Acidification	0.017411948
Climate change	0.083574719
Ecotoxicity, freshwater	0.006899855
Eutrophication, freshwater	0.002308509
Eutrophication, marine	0.004014143
Eutrophication, terrestrial	0.006057591
Human toxicity, cancer	0.001611048
Human toxicity, non-cancer	0.002792634
Ionising radiation	0.00950662
Land use	0.000626264
Ozone depletion	0.00056178
Particulate matter	0.020184914
Photochemical ozone formation	0.010795318
Resource use, fossils	0.07683587
Resource use, minerals and metals	0.002357401
Water use	1.272102218

Table A3

Normalized environmental impact assessment across various categories in Pt units

Impact category	Normalized results in Pt
Acidification	0.280837867
Climate change	0.39684102
Ecotoxicity, freshwater	0.359367438
Eutrophication, freshwater	0.082446754
Eutrophication, marine	0.135612951
Eutrophication, terrestrial	0.16327738
Human toxicity, cancer	0.075636074
Human toxicity, non-cancer	0.151773563
Ionising radiation	0.189752891
Land use	0.00788745
Ozone depletion	0.008903003
Particulate matter	0.225278059
Photochemical ozone formation	0.225843482
Resource use, fossils	0.923508053
Resource use, minerals and metals	0.031223858
Water use	14.94832219

Data availability

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

References

- Abel, E.E., Shafie, A.L.M., Chan, W.H., 2021. Deployment of internet of things-based cloudlet-cloud for surveillance operations. *IAES Int. J. Artif. Intell.* 10 (1), 24. <https://doi.org/10.11591/ijai.v10.i1.pp24-34>.
- Agrawal, A., Chopra, S., 2020. Sustainable dyeing of selected natural and synthetic fabrics using waste teak leaves (*Tectona Grandis L.*). *Research Journal of Textile and Apparel* 24 (4), 357–374. <https://doi.org/10.1108/rjta-05-2020-0046>.
- Ahmad, S., Miskon, S., Alabdan, R., Tlili, I., 2021. Statistical assessment of business intelligence system adoption model for sustainable textile and apparel industry. *IEEE Access* 9, 106560–106574. <https://doi.org/10.1109/access.2021.3100410>.
- Ahmed, W., MacCarthy, B., 2021. Blockchain-enabled supply chain traceability in the textile and apparel supply chain: a case study of the fiber producer, lenzing. *Sustainability* 13 (19), 10496. <https://doi.org/10.3390/su131910496>.
- Ahmed, S., Kalsoom, T., Ramzan, N., Pervez, Z., Azmat, M., Zeb, B., Ur-Rehman, M., 2021. Towards supply chain visibility using internet of things: a Dyadic analysis review. *Sensors* 21 (12), 4158. <https://doi.org/10.3390/s21124158>.
- Akram, S.V., Singh, R., Gehlot, A., Rashid, M., AlGhamdi, A.S., Alshamrani, S.S., Prashar, D., 2021. Role of wireless aided technologies in the solid waste management: a comprehensive review. *Sustainability* 13 (23), 13104. <https://doi.org/10.3390/su132313104>.
- Akter, N., Baral, L.M., Auntu, S.K., Alim, M.A., Rashed, M.F.R., 2022. Exploration of barriers and success factors of sustainability at producer level in textile industry: a study of Bangladesh perspective. *Textile & Leather Review* 5, 430–450. <https://doi.org/10.31881/tlr.2022.40>.
- Aldabahi, A., El-Naggar, M.E., El-Newehy, M.H., Rahaman, M., Hatshan, M.R., Khattab, T.A., 2021. Effects of technical textiles and synthetic nanofibers on environmental pollution. *Polymers* 13 (1), 155. <https://doi.org/10.3390/polym13010155>.
- Ali, A., Haseeb, M., 2019. Radio frequency identification (rfid) technology as a strategic tool towards higher performance of supply chain operations in textile and apparel industry of Malaysia. *Uncertain Supply Chain Management* 215–226. <https://doi.org/10.5267/j.uscm.2018.10.004>.
- Amutha, K., Annaporani, S., Sakthivel, P., Sudhapriya, N., 2022. Ecofriendly dyeing of textiles with natural dyes extracted from commercial food processing waste materials. *J. Nat. Fibers* 19 (15), 10394–10411. <https://doi.org/10.1080/15440478.2021.1993506>.
- Andrade, C., Perestrelo, R., Câmara, J., 2022. Bioactive compounds and antioxidant activity from spent coffee grounds as a powerful approach for its valorization. *Molecules* 27 (21), 7504. <https://doi.org/10.3390/molecules27217504>.
- Arnold, M.G., Pfaff, C., Pfaff, T.J., 2023. Circular business model strategies Progressing sustainability in the German textile manufacturing industry. *Sustainability* 15 (5), 4595. <https://doi.org/10.3390/su15054595>.
- Arrigo, E., 2020. Global sourcing in Fast fashion Retailers: sourcing locations and sustainability considerations. *Sustainability* 12 (2), 508. <https://doi.org/10.3390/su12020508>.
- Awan, U., Sroufe, R., Shahbaz, M., 2021. Industry 4.0 and the circular economy: a literature review and recommendations for future research. *Bus. Strat. Environ.* 30 (4), 2038–2060. <https://doi.org/10.1002/bse.2731>.
- Babu, S., Kumar, P., Devi, B.S., Reddy, K.P., Satish, M., Prakash, A., 2023. Enhancing efficiency and productivity: IoT in industrial manufacturing. In: *IEEE 5th International Conference on Cybernetics, Cognition and Machine Learning Applications (ICCCMLA)*. <https://doi.org/10.1109/icccmla58983.2023.10346807>.
- Badhwar, A., Islam, S., Tan, C., 2023. Exploring the potential of blockchain technology within the fashion and textile supply chain with a focus on traceability,

- transparency, and product authenticity: a systematic review. *Frontiers in Blockchain* 6. <https://doi.org/10.3389/fbloc.2023.1044723>.
- Bae, J., Hong, K.H., 2019. Optimized dyeing process for enhancing the functionalities of spent coffee dyed wool fabrics using a facile extraction process. *Polymers* 11 (4), 574. <https://doi.org/10.3390/polym11040574>.
- Balfaqih, M., Balfagih, Z., Lytras, M.D., Alfawaz, K.M., Alshdadi, A.A., Alsolami, E., 2023. A Blockchain-Enabled IoT logistics system for efficient tracking and management of High-Price shipments: a resilient, scalable and sustainable approach to smart cities. *Sustainability* 15 (18), 13971. <https://doi.org/10.3390/su151813971>.
- Barna, L., Ionescu, B.Ş., Feleagă, L., 2021. The relationship between the implementation of ERP systems and the financial and non-financial reporting of organizations. *Sustainability* 13 (21), 11566. <https://doi.org/10.3390/su132111566>.
- Benachio, G.L.F., Freitas, M.D.C.D., Tavares, S.F., 2020. Circular economy in the construction industry: a systematic literature review. *J. Clean. Prod.* 260, 121046. <https://doi.org/10.1016/j.jclepro.2020.121046>.
- Bottani, E., Tebaldi, L., Volpi, A., 2019. The role of ICT in supporting spent coffee grounds collection and valorization: a quantitative assessment. *Sustainability* 11 (23), 6572. <https://doi.org/10.3390/su11236572>.
- Bressaneli, G., Pigosso, D.C.A., Sacconi, N., Perona, M., 2021. Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: a literature review. *J. Clean. Prod.* 298, 126819. <https://doi.org/10.1016/j.jclepro.2021.126819>.
- Bruce, M., Daly, L., Towers, N., 2004. Lean or agile: a solution for supply chain management in the textiles and clothing industry? *Int. J. Oper. Prod. Manag.* 24 (2), 151–170. <https://doi.org/10.1108/01443570410514867>.
- Brun, A., Karasman, H., Barresi, T., 2020. Supply chain collaboration for transparency. *Sustainability* 12 (11), 4429. <https://doi.org/10.3390/su12114429>.
- Calheiros, D., Dias, M., Calhelha, R., Barros, L., Ferreira, I., Fernandes, C., et al., 2023. Antifungal activity of spent coffee ground extracts. *Microorganisms* 11 (2), 242. <https://doi.org/10.3390/microorganisms11020242>.
- Cao, H., Cobb, K., Yatvitskiy, M., Wolfe, M., Shen, H., 2022. Textile and product development from end-of-use cotton apparel: a study to reclaim value from waste. *Sustainability* 14 (14), 8553. <https://doi.org/10.3390/su14148553>.
- Car, T., Stifanich, L.P., Šimunić, M., 2019. Internet of things (IoT) in tourism and hospitality: OPPORTUNITIES and challenges. *Tourism in south east europe. Tourism in Southern and Eastern Europe*. <https://doi.org/10.20867/tosee.05.42>.
- Carnley, P.R., Kettani, H., 2019. Identity and access management for the internet of things. *International Journal of Future Computer and Communication* 8 (4), 129–133. <https://doi.org/10.18178/ijfcc.2019.8.4.554>.
- Carrières, V., Lemieux, A., Margni, M., Pellerin, R., Cariou, S., 2022. Measuring the value of blockchain traceability in supporting LCA for textile products. *Sustainability* 14 (4), 2109. <https://doi.org/10.3390/su14042109>.
- Cil, I., Arisoy, F., Kiliç, H., 2021. Visibility of resources and assets in the shipyard through industrial internet of things. *Global Journal of Computer Sciences* 11 (2), 88–101. <https://doi.org/10.18844/gjcs.v11i2.5429>.
- De Vass, T., Shee, H., Miah, S.J., 2020. IoT in supply chain management: a narrative on retail sector sustainability. *Int. J. Logist.* 24 (6), 605–624. <https://doi.org/10.1080/13675567.2020.1787970>.
- Desore, A., Narula, S.A., 2018. An overview on corporate response towards sustainability issues in textile industry. *Environ. Dev. Sustain.* 20 (4), 1439–1459. <https://doi.org/10.1007/s10668-017-9949-1>.
- Devi, O.R., 2020. New sustainable fibres and their application in textiles: a review. *International Journal of Modern Trends in Science and Technology* 6 (9S), 136–141. <https://doi.org/10.46501/ijmst0609s22>.
- Dhonde, B., Patel, C.R., 2020. Implementing circular economy concepts for sustainable urban freight transport: case of textile manufacturing supply chain. *Acta Logistica* 7 (2), 131–143. <https://doi.org/10.22306/al.v7i2.172>.
- Ding, X., Liu, N., Guo, C., Jia, D., Guo, N., Wang, L., 2023. Synergistic effects between lignin, cellulose and coal in the co-pyrolysis process of coal and cotton stalk. *Molecules* 28 (15), 5708. <https://doi.org/10.3390/molecules28155708>.
- Duguma, A., 2024. Biogas production through anaerobic codigestion of distillery wastewater sludge and disposable spent yeast. *Int. J. Chem. Eng.* 2024, 1–16. <https://doi.org/10.1155/2024/5510471>.
- Espósito, B., Sessa, M.R., Sica, D., Malandrino, O., 2020. Towards circular economy in the agri-food sector. A systematic literature review. *Sustainability* 12 (18), 7401. <https://doi.org/10.3390/su12187401>.
- Fatima, Z., Tanveer, M.H., Waseemullah, W., Zardari, S., Naz, L.F., Khadim, H., Ahmed, N., Tahir, M., 2022. Production plant and warehouse automation with IoT and industry 5.0. *Appl. Sci.* 12 (4), 2053. <https://doi.org/10.3390/app12042053>.
- Franca, A.S., Oliveira, L.S., 2022. Potential uses of spent coffee grounds in the food industry. *Foods* 11 (14), 2064. <https://doi.org/10.3390/foods11142064>.
- Furberg, A., Arvidsson, R., Molander, S., 2021. A practice-based framework for defining functional units in comparative life cycle assessments of materials. *J. Ind. Ecol.* 26 (3), 718–730. <https://doi.org/10.1111/jiec.13218>.
- Furferi, R., Volpe, Y., Mantellassi, F., 2022. Circular economy guidelines for the textile industry. *Sustainability* 14 (17), 11111. <https://doi.org/10.3390/su141711111>.
- Gbadamosi, A., Oyedele, L., Delgado, J., Kusimo, H., Akànbí, L., Olawale, O., Muhammed-yakubu, N., 2021. IoT for predictive assets monitoring and maintenance: an implementation strategy for the UK rail industry. *Autom. Construct.* 122, 103486. <https://doi.org/10.1016/j.autcon.2020.103486>.
- Gebhardt, M., Kopyto, M., Birkel, H., Hartmann, E., 2021. Industry 4.0 technologies as enablers of collaboration in circular supply chains: a systematic literature review. *Int. J. Prod. Res.* 60 (23), 6967–6995. <https://doi.org/10.1080/00207543.2021.1999521>.
- Gebreyessus, G.D., 2022. Towards the sustainable and circular bioeconomy: insights on spent coffee grounds valorization. *Sci. Total Environ.* 833, 155113. <https://doi.org/10.1016/j.scitotenv.2022.155113>.
- Gharaibeh, L., Eriksson, K., Lantz, B., 2022. Supply chain digitalization in the wood manufacturing industry: a bibliometric literature review. <https://doi.org/10.3233/atde220180>.
- Goodman, M.S., Ackermann, N., Bowen, D.J., Thompson, V.L.S., 2019. Content validation of a quantitative stakeholder engagement measure. *J. Community Psychol.* 47 (8), 1937–1951. <https://doi.org/10.1002/jcop.22239>.
- Gunasekaran, K., Kumar, V.V., Kaladevi, A.C., Mahesh, T.R., Bhat, C.R., Venkatesan, K., 2023. Smart Decision-Making and communication strategy in industrial internet of things. *IEEE Access* 11, 28222–28235. <https://doi.org/10.1109/access.2023.3258407>.
- Hafeez, T., Xu, L., McArdle, G., 2021. Edge Intelligence for data handling and predictive maintenance in IIOT. *IEEE Access* 9, 49355–49371. <https://doi.org/10.1109/access.2021.3069137>.
- Haji, A., Naebe, M., 2020. Cleaner dyeing of textiles using plasma treatment and natural dyes: a review. *J. Clean. Prod.* 265, 121866. <https://doi.org/10.1016/j.jclepro.2020.121866>.
- Haji, A., Rahimi, M., 2020. RSM optimization of wool dyeing with berberis thunbergii DC leaves as a new source of natural dye. *J. Nat. Fibers* 19 (8), 2785–2798. <https://doi.org/10.1080/15440478.2020.1821293>.
- Haricha, K., Khait, A., Issaoui, Y., Bahasse, A., Ouajji, H., 2021. Towards smart manufacturing: implementation and benefits. *International Journal of Ubiquitous Systems and Pervasive Networks* 15 (2), 25–31. <https://doi.org/10.5383/juspn.15.02.004>.
- Hong, K.H., 2018. Effects of tannin mordanting on coloring and functionalities of wool fabrics dyed with spent coffee grounds. *Fashion and Textiles* 5 (1). <https://doi.org/10.1186/s40691-018-0151-3>.
- Hu, Y., Gallant, R.K., Salaudeen, S.A., Farooque, A.A., He, Q., 2022. Hydrothermal carbonization of spent coffee grounds for producing solid fuel. *Sustainability* 14 (14), 8818. <https://doi.org/10.3390/su14148818>.
- Hussain, D., Figueiredo, M., 2023. Improving the time-based performance of the preparatory stage in textile manufacturing process with value stream mapping. *Bus. Process Manag. J.* 29 (3), 801–837. <https://doi.org/10.1108/bpmj-08-2022-0366>.
- Iftikhar, A., Cui, X., Yang, Y., 2021. Blockchain technology for trustworthy operations in the management of strategic grain reserves. *Foods* 10 (10), 2323. <https://doi.org/10.3390/foods10102323>.
- Jain, T., Jain, J.K., Agrawal, R., Johri, S., 2022. Investigation of environmental potentials on supply chain of textile and yarn industry using smart and sustainable life cycle assessment. *Management of Environmental Quality* 34 (4), 902–925. <https://doi.org/10.1108/meq-03-2022-0062>.
- Jia, F., Yin, S., Chen, L., Chen, X., 2020. The circular economy in the textile and apparel industry: a systematic literature review. *J. Clean. Prod.* 259, 120728. <https://doi.org/10.1016/j.jclepro.2020.120728>.
- Jia, D., Zhang, H., Han, X., 2023. Construction of enterprise marketing management system in digital economic environment from the perspective of green ecology. *Sustainability* 15 (2), 1299. <https://doi.org/10.3390/su15021299>.
- Karayılan, S., Yılmaz, O., Uysal, Ç., Naneci, S., 2021. Prospective evaluation of circular economy practices within plastic packaging value chain through optimization of life cycle impacts and circularity. *Resour. Conserv. Recycl.* 173, 105691. <https://doi.org/10.1016/j.resconrec.2021.105691>.
- Kazancoglu, I., Kazancoglu, Y., Yarımoğlu, E., Kahraman, A., 2020. A conceptual framework for barriers of circular supply chains for sustainability in the textile industry. *Sustain. Dev.* 28 (5), 1477–1492. <https://doi.org/10.1002/sd.2100>.
- Keshav, P., Banoth, C., Kethavath, S., Bhukya, B., 2021. Lignocellulosic ethanol production from cotton stalk: an overview on pretreatment, saccharification and fermentation methods for improved bioconversion process. *Biomass Conversion and Biorefinery* 13 (6), 4477–4493. <https://doi.org/10.1007/s13399-021-01468-z>.
- Khan, Y., Su'ud, M.B.M., Alam, M.M., Ahmad, S.F., Ahmad, A.Y.a.B., Khan, N., 2022. Application of Internet of Things (IoT) in sustainable supply chain management. *Sustainability* 15 (1), 694. <https://doi.org/10.3390/su15010694>.
- Khan, S., Khan, S.A., Kamal, M.A., Syed, A.A., 2023. Competitiveness analysis of Pakistan's cotton yarn exports relative to India and USA: a demand system application with focuses on China's market. *Glob. Bus. Rev.* <https://doi.org/10.1177/09721509231199302>.
- Kim, H., Kim, H.R., 2022. Production of coffee-dyed bacterial cellulose as a bio-leather and using it as a dye adsorbent. *PLoS One* 17 (3), e0265743. <https://doi.org/10.1371/journal.pone.0265743>.
- Kiran, S., Adeel, S., Yousef, M.S., Habib, N., Hassan, A., Qayyum, M.A., Abdullah, M., 2020. Green dyeing of microwave treated silk using coconut coir-based tannin natural dye. *Industria Textila* 71 (3), 227–234. <https://doi.org/10.35530/it.071.03.1666>.
- Koh, E., Hong, K.H., 2017. Preparation and properties of cotton fabrics finished with spent coffee extract. *Cellulose* 24 (11), 5225–5232. <https://doi.org/10.1007/s10570-017-1466-8>.
- Kumar, N.M., Chopra, S.S., 2022. Leveraging blockchain and smart contract technologies to overcome circular economy implementation challenges. *Sustainability* 14 (15), 9492. <https://doi.org/10.3390/su14159492>.
- Kumar, D.V., Mohan, G.M., Sundaram, K.M., 2020. Lean supply chain management in garment industry using value stream mapping. *Int. J. Serv. Oper. Manag.* 37 (1), 133. <https://doi.org/10.1504/ijom.2020.10031555>.
- Kumar, N., Garg, P., Singh, S., 2022. Pro-environmental purchase intention towards eco-friendly apparel: augmenting the theory of planned behavior with perceived consumer effectiveness and environmental concern. *Journal of Global Fashion Marketing* 13 (2), 134–150. <https://doi.org/10.1080/20932685.2021.2016062>.

- Lee, Y., 2006. Dyeing, fastness, and deodorizing properties of cotton, silk, and wool fabrics dyed with coffee sludge (*Coffea arabica* L.) extract. *J. Appl. Polym. Sci.* 103 (1), 251–257. <https://doi.org/10.1002/app.25221>.
- Leow, Y., Yew, P.Y.M., Chee, P.L., Loh, X.J., Kai, D., 2021. Recycling of spent coffee grounds for useful extracts and green composites. *RSC Adv.* 11 (5), 2682–2692. <https://doi.org/10.1039/d0ra09379c>.
- Li, R., Liu, W., Zhou, S., 2024. Digital transformation of supply chain management in the fast fashion industry: a case study of Zara. *SHS Web of Conferences* 181, 04019. <https://doi.org/10.1051/shsconf/202418104019>.
- Liu, L., Mishra, A.R., 2022. Enabling technologies challenges of green internet of things (IoT) towards sustainable development in the era of industry 4.0. *Technol. Econ. Dev. Econ.* 0 (0), 1–32. <https://doi.org/10.3846/tede.2022.16520>.
- López, T., Riedler, T., Köhnen, H., Fütterer, M., 2021. Digital value chain restructuring and labour process transformations in the fast-fashion sector: evidence from the value chains of Zara & H&M. *Glob. Netw.* 22 (4), 684–700. <https://doi.org/10.1111/glob.12353>.
- Loser, A., Witzke, J., Schintke, F., Scheuermann, B., 2022. BottleMod: modeling data flows and tasks for fast bottleneck analysis. 2022 IEEE International Conference on Big Data (Big Data). <https://doi.org/10.1109/bigdata55660.2022.10020255>.
- Luque, A., Herrero-García, N., 2019. How corporate social (ir)responsibility in the textile sector is defined, and its impact on ethical sustainability: an analysis of 133 concepts. *Corp. Soc. Responsib. Environ. Manag.* 26 (6), 1285–1306. <https://doi.org/10.1002/csr.1747>.
- Madhav, S., Ahamad, A., Singh, P., Mishra, P.K., 2018. A review of textile industry: wet processing, environmental impacts, and effluent treatment methods. *Environ. Qual. Manag.* 27 (3), 31–41. <https://doi.org/10.1002/tqem.21538>.
- Magrini, C., Nicolas, J., Berg, H., Bellini, A., Paolini, E., Vincenti, N., Campadello, L., Bonoli, A., 2021. Using internet of things and distributed ledger technology for digital circular economy enablement: the case of electronic equipment. *Sustainability* 13 (9), 4982. <https://doi.org/10.3390/su13094982>.
- Manglani, H., Hodge, G.L., Oxenham, W., 2019. Application of the internet of things in the textile industry. *Textil. Prog.* 51 (3), 225–297. <https://doi.org/10.1080/00405167.2020.1763701>.
- Manickam, P., Vijay, D., 2021. Chemical Hazards in Textiles. Elsevier eBooks, pp. 19–52. <https://doi.org/10.1016/b978-0-12-820494-8.00002-2>.
- Maouchi, M., Ersoy, O., Erkin, Z., 2018. TRADE: a transparent, decentralized traceability system for the supply chain. <https://doi.org/10.18420/BLOCKCHAIN2018.01>.
- Matis, Y., Krot, O., 2021. PRODUCT LIFE CYCLE ASSESSMENT METHOD AS AN EFFECTIVE COMPLEX OF ACTIONS REGARDING THE ECO-SAFETY OF THE CHEMICAL INDUSTRY, vol. 9. *Tehnoogeno-ekologična Bezpeka*, pp. 52–57. <https://doi.org/10.52363/2522-1892.2021.1.8.1/2021>.
- McKenna, J., 2018. 5 Innovative Ways Your Coffee Grounds Can Be Recycled. *World Economic Forum*. <https://www.weforum.org/agenda/2018/11/5-surprising-ways-coffee-grounds-can-be-reused/>.
- Mercan, S., Cain, L., Akkaya, K., Cebe, M., Uluagac, S., Alonso, M.Á.V., Çobanoğlu, C., 2020. Improving the service industry with hyper-connectivity: IoT in hospitality. *Int. J. Contemp. Hospit. Manag.* 33 (1), 243–262. <https://doi.org/10.1108/ijchm-06-2020-0621>.
- Ministry of Commerce, 2022. <https://www.commerce.gov.pk/wp-content/uploads/2022/02/Textiles-and-Apparel-Policy-2020-25.pdf>.
- Mirani, A.A., Velasco-Hernandez, G., Awasthi, A., Walsh, J., 2022. Key challenges and emerging technologies in industrial IoT architectures: a review. *Sensors* 22 (15), 5836. <https://doi.org/10.3390/s22155836>.
- Mongkolrattanasit, R., Nakpathom, M., Uthiganon, N., 2021. Eco-dyeing with biocolourant from spent coffee ground on low molecular weight chitosan crosslinked cotton. *Sustainable Chemistry and Pharmacy* 20, 100389. <https://doi.org/10.1016/j.scp.2021.100389>.
- Moosavi, J., Naeni, L.M., Fathollahi-Fard, A.M., Fiore, U., 2021. Blockchain in supply chain management: a review, bibliometric, and network analysis. *Environ. Sci. Pollut. Res. Int.* <https://doi.org/10.1007/s11356-021-13094-3>.
- Mostafa, N., Hamdy, W., Alawady, H., 2019. Impacts of internet of things on supply chains: a framework for warehousing. *Soc. Sci.* 8 (3), 84. <https://doi.org/10.3390/socsci8030084>.
- Nam, C., Xiang, C., 2019. Natural dyeing application of used coffee grounds as a potential resource. *International Journal of Fashion Design, Technology and Education* 12 (3), 335–345. <https://doi.org/10.1080/17543266.2019.1640291>.
- Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., Gwilt, A., 2020. The environmental price of fast fashion. *Nat. Rev. Earth Environ.* 1 (4), 189–200. <https://doi.org/10.1038/s43017-020-0039-9>.
- Oelze, N., 2017. Sustainable supply chain management implementation—enablers and barriers in the textile industry. *Sustainability* 9 (8), 1435. <https://doi.org/10.3390/su9081435>.
- Osaretin, C., Zamanlou, M., Iqbal, M., Butt, S., 2020. Open source IoT-based SCADA system for remote oil facilities using node-RED and arduino microcontrollers. 2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), pp. 571–575. <https://doi.org/10.1109/IEMCON51383.2020.9284826>.
- Pakseresh, A., Kaliji, S.A., Xhakollari, V., 2022. How blockchain facilitates the transition toward circular economy in the food chain? *Sustainability* 14 (18), 11754. <https://doi.org/10.3390/su141811754>.
- Panasa, A., Zuurro, A., Lavecchia, R., Marroso, G., Petrucci, R., 2013. Recovery of natural antioxidants from spent coffee grounds. *J. Agric. Food Chem.* 61 (17), 4162–4168. <https://doi.org/10.1021/jf4005719>.
- Papasolomou, I., Melanthiou, Y., Tsamouridis, A., 2022. The fast fashion vs environment debate: consumers' level of awareness, feelings, and behaviour towards sustainability within the fast-fashion sector. *J. Market. Commun.* 1–19. <https://doi.org/10.1080/13527266.2022.2154059>.
- Patti, A., Aciermo, D., 2022. Towards the sustainability of the plastic industry through biopolymers: properties and potential applications to the textiles world. *Polymers* 14 (4), 692. <https://doi.org/10.3390/polym14040692>.
- Patti, A., Cicala, G., Aciermo, D., 2020. Eco-Sustainability of the textile production: waste recovery and current recycling in the composites world. *Polymers* 13 (1), 134. <https://doi.org/10.3390/polym13010134>.
- Pattnaik, P., Dangayach, G., Bhardwaj, A.K., 2018. A review on the sustainability of textile industries wastewater with and without treatment methodologies. *Rev. Environ. Health* 33 (2), 163–203. <https://doi.org/10.1515/revh-2018-0013>.
- Pedersen, E.R.G., Andersen, K.R., 2015. Sustainability innovators and anchor draggers: a global expert study on sustainable fashion. *J. Fash. Mark. Manag.* 19 (3), 315–327. <https://doi.org/10.1108/jfmm-08-2014-0059>.
- Petrillo, A., Colangelo, F., Farina, I., Travagliani, M., Salzano, C., Cioffi, R., 2022. Multi-criteria analysis for Life Cycle Assessment and Life Cycle Costing of lightweight artificial aggregates from industrial waste by double-step cold bonding palletization. *J. Clean. Prod.* 351, 131395. <https://doi.org/10.1016/j.jclepro.2022.131395>.
- Provin, A.P., De Aguiar Dutra, A.R., Machado, M.M., Cubas, A.L.V., 2021. New materials for clothing: rethinking possibilities through a sustainability approach - a review. *J. Clean. Prod.* 282, 124444. <https://doi.org/10.1016/j.jclepro.2020.124444>.
- Qin, Y., Liu, H., 2022. Application of value stream mapping in E-Commerce: a case study on the Amazon retailer. *Sustainability* 14 (2), 713. <https://doi.org/10.3390/su14020713>.
- Rahaman, T., Khan, S.H., 2024. Green merchandising of textiles and apparel in a circular economy: recent trends, framework, challenges and future prospects towards sustainability. *Journal of Open Innovation Technology Market and Complexity*, 100457. <https://doi.org/10.1016/j.joitmc.2024.100457>.
- Rehman, M., Petrillo, A., Ortíz-Barrios, M., Forcina, A., Baffo, I., De Felice, F., 2024. Sustainable fashion: mapping waste streams and life cycle management. *J. Clean. Prod.* 444, 141279. <https://doi.org/10.1016/j.jclepro.2024.141279>.
- Rejeb, A., Rejeb, K., Keogh, J.G., Zailani, S., 2022. Barriers to blockchain adoption in the circular Economy: a fuzzy Delphi and Best-Worst approach. *Sustainability* 14 (6), 3611. <https://doi.org/10.3390/su14063611>.
- Rett, J.P., Traoré, Y.L., Ho, E.A., 2021. Sustainable materials for fused deposition modeling 3D printing applications. *Adv. Eng. Mater.* 23 (7). <https://doi.org/10.1002/adem.202001472>.
- Rivera, X.S., Gallego-Schmid, A., Najdanovic-Visak, V., Azapagic, A., 2020. Life cycle environmental sustainability of valorisation routes for spent coffee grounds: from waste to resources. *Resour. Conserv. Recycl.* 157, 104751. <https://doi.org/10.1016/j.resconrec.2020.104751>.
- Ronga, D., Parisi, M., Barbieri, L., Lancellotti, I., Andreola, F., Bignami, C., 2020. Valorization of spent coffee grounds, biochar and other residues to produce lightweight clay ceramic aggregates suitable for nursery grapevine production. *Horticulturae* 6 (4), 58. <https://doi.org/10.3390/horticulturae6040058>.
- Roy, M., Sen, P., Pal, P., 2020. An integrated green management model to improve environmental performance of textile industry towards sustainability. *J. Clean. Prod.* 271, 122656. <https://doi.org/10.1016/j.jclepro.2020.122656>.
- Saberian, M., Li, J., Donnoli, A., Bondarenko, E., Oliva, P., Gill, B.P., Lockrey, S., Siddique, R., 2021. Recycling of spent coffee grounds in construction materials: a review. *J. Clean. Prod.* 289, 125837. <https://doi.org/10.1016/j.jclepro.2021.125837>.
- Sahu, A., Agrawal, S., Kumar, G., 2021. Integrating Industry 4.0 and circular economy: a review. *J. Enterprise Inf. Manag.* 35 (3), 885–917. <https://doi.org/10.1108/jeim-11-2020-0465>.
- Salo, H.H., Suikkanen, J., Nissinen, A., 2020. Eco-innovation motivations and ecodesign tool implementation in companies in the Nordic textile and information technology sectors. *Bus. Strat. Environ.* 29 (6), 2654–2667. <https://doi.org/10.1002/bse.2527>.
- Saratale, G.D., Bhosale, R.R., Shobana, S., Banu, J.R., Pugazhendhi, A., Mahmood, E., Sirohi, R., Bhatia, S.K., Atabani, A., Mulone, V., Yoon, J.J., Shin, H.S., Kumar, G., 2020. A review on valorization of spent coffee grounds (SCG) towards biopolymers and biocatalysts production. *Bioresour. Technol.* 314, 123800. <https://doi.org/10.1016/j.biortech.2020.123800>.
- Sardar, S., Mohsin, M., Memon, M.S., Ramzan, B., Sharif, R., 2022. An empirical study regarding the environmental sustainability practices in the textile industry. *Industria Textila* 73 (4), 384–396. <https://doi.org/10.35530/it.073.04.202152>.
- Schettino, R., Verni, M., Vincentini, O., Krona, A., Knaapila, A., Cagno, R., et al., 2021. Bioprocessed brewers' spent grain improves nutritional and antioxidant properties of pasta. *Antioxidants* 10 (5), 742. <https://doi.org/10.3390/antiox10050742>.
- Sharma, Y., Tyagi, V., Datta, P.C., 2020. IOT based smart agriculture monitoring system. *Int. J. Innovative Technol. Explor. Eng.* 9 (9), 325–328. <https://doi.org/10.35940/ijitee.i7142.079920>.
- Shen, B., Li, Q., Dong, C., Perry, P., 2017. Sustainability issues in textile and apparel supply chains. *Sustainability* 9 (9), 1592. <https://doi.org/10.3390/su9091592>.
- Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., Naebe, M., 2020. Death by waste: fashion and textile circular economy case. *Sci. Total Environ.* 718, 137317. <https://doi.org/10.1016/j.scitotenv.2020.137317>.
- Simpkin, C., Taylor, I., Harborne, D., Bent, G., Preece, A., Ganti, R., 2020. Efficient orchestration of node-RED IoT workflows using a vector symbolic architecture. *Future Gener. Comput. Syst.* 111, 117–131. <https://doi.org/10.1016/j.future.2020.04.005>.
- Singh, M., Vajpayee, M., Ledwani, L., 2021. Eco-friendly surface modification of natural fibres to improve dye uptake using natural dyes and application of natural dyes in fabric finishing: a review. *Mater. Today Proc.* 43, 2868–2871. <https://doi.org/10.1016/j.matpr.2021.01.078>.

- Sinha, P., Sharma, M., Agrawal, R., 2022. A systematic review and future research agenda for sustainable fashion in the apparel industry. *Benchmarking* 30 (9), 3482–3507. <https://doi.org/10.1108/bij-02-2022-0142>.
- Sun, X., Wang, X., 2022. Modeling and analyzing the impact of the internet of things-based industry 4.0 on circular economy practices for sustainable development: evidence from the food processing industry of China. *Front. Psychol.* 13. <https://doi.org/10.3389/fpsyg.2022.866361>.
- Tariq, H., Ali, Y., Khan, A.U., Petrillo, A., De Felice, F., 2021. Sustainable production of diapers and their potential outputs for the Pakistani market in the circular economy perspective. *Sci. Total Environ.* 769, 145084. <https://doi.org/10.1016/j.scitotenv.2021.145084>.
- Tasneem, F., Khan, M.A., 2024. Growth and structural transformation – options for Pakistan. *Research in Globalization* 8, 100190. <https://doi.org/10.1016/j.resglo.2023.100190>.
- TextileMates, 2019. Coffee ground fibre – a most worthwhile fibre. *Fibre2Fashion*. <https://www.fibre2fashion.com/industry-article/8379/coffee-ground-fibre-a-most-worth-while-fibre>.
- Tyagi, N., Singh, J., Singh, S., 2022. Sensor based wearable devices for road navigation. *ECS Trans.* 107 (1), 8863–8869. <https://doi.org/10.1149/10701.8863ecst>.
- Uddin, A.S., Ali, Y., Sabir, M., Petrillo, A., De Felice, F., 2023. Circular economy and its implementation in cement industry: a case point in Pakistan. *Sci. Total Environ.* 898, 165605. <https://doi.org/10.1016/j.scitotenv.2023.165605>.
- Upadhyay, A., Mukhty, S., Kumar, V., Kazançoğlu, Y., 2021. Blockchain technology and the circular economy: implications for sustainability and social responsibility. *J. Clean. Prod.* 293, 126130. <https://doi.org/10.1016/j.jclepro.2021.126130>.
- Wagner, M., Heinzl, T., 2020. Human perceptions of recycled textiles and circular fashion: a systematic literature review. *Sustainability* 12 (24), 10599. <https://doi.org/10.3390/su122410599>.
- Wahab, A., Hussain, T., 2020. Eco-Friendly garment processing using aerosol technology. *Water Resour. Ind.* 23, 100127. <https://doi.org/10.1016/j.wri.2020.100127>.
- Wang, B., Luo, W., Zhang, A., Tian, Z., Li, Z., 2020. Blockchain-enabled circular supply chain management: a system architecture for fast fashion. *Comput. Ind.* 123, 103324. <https://doi.org/10.1016/j.compind.2020.103324>.
- Wiedemann, S., Van Nguyen, Q., Clarke, S.J., 2022. Using LCA and circularity indicators to measure the sustainability of textiles—examples of renewable and non-renewable fibres. *Sustainability* 14 (24), 16683. <https://doi.org/10.3390/su142416683>.
- Wynn, M., Jones, P., 2022. Digital technology deployment and the circular economy. *Sustainability* 14 (15), 9077. <https://doi.org/10.3390/su14159077>.
- Yang, Q., Samson, A., Gummi, U., Chen, D., 2023. Study on the use of industry 4.0 technology for the textile industry sustainable supply chain process. *Advances in Engineering Technology Research* 4 (1), 140. <https://doi.org/10.56028/aetr.4.1.140.2023>.
- Zandberga, A., Kalnins, S., Gusca, J., 2023. Decision-making algorithm for waste recovery options. review on textile waste derived products. *Environmental and Climate Technologies* 27 (1), 137–149. <https://doi.org/10.2478/rtuct-2023-0011>.
- Zayed, B.A., Talaia, A.M., Gaaboobah, M.A., Amer, S.M., Mansour, F.R., 2023. Google Trends as a predictive tool in the era of COVID-19: a scoping review. *Postgrad. Med. J.* 99 (1175), 962–975. <https://doi.org/10.1093/postmj/qgad012>.
- Zdravković, M., Panetto, H., Weichhart, G., 2021. AI-Enabled enterprise information systems for manufacturing. *Enterp. Inf. Syst.* 16 (4), 668–720. <https://doi.org/10.1080/17517575.2021.1941275>.
- Zhou, B., Li, W., Ma, G., Zhao, X., Zhao, X., 2020. Preparation and properties of biogeopolymer composites with waste cotton stalk materials. *J. Clean. Prod.* 245, 118842. <https://doi.org/10.1016/j.jclepro.2019.118842>.
- Zubaydi, H.D., Varga, P., Molnár, S., 2023. Leveraging blockchain technology for ensuring security and privacy aspects in Internet of Things: a Systematic Literature review. *Sensors* 23 (2), 788. <https://doi.org/10.3390/s23020788>.