NIFT JOURNAL OF FASHION

VOLUME 4

2025

NIFT Journal of Fashion

Volume 4, 2025

Fashion in Transition: The Confluence of Handmade and Technology

National Institute of Fashion Technology
https://nift.ac.in/journaloffashion

NIFT Journal of Fashion
Volume 4, 2025
editor.njf@nift.ac.in
https://nift.ac.in/journaloffashion
ISSN 2583-5262 (Print)
ISSN 3048-7307 (Electronic)

Printed and Published by
Suresh Kumar
on behalf of National Institute of Fashion Technology
Hauz Khas, New Delhi – 110016

Printed at
Reckon Enterprises
A-11, Shahdara, East Delhi - 110095

Editor
Ruby Kashyap Sood

Cover design: *Dimple Bahl*, Head - Corporate Communication Cell

Editorial Board

MESSAGE

It gives me immense pleasure to present the fourth volume of the NIFT Journal of Fashion that centers on a very pertinent theme that discusses the integration of handcrafted traditions and technological innovation, two important pillars molding the fashion ecosystem. In today's time, when caring for the planet is most crucial, the appreciation of craft heritage and handmade skills is growing manifold and given due attention by countries across the globe. Yet, the fast-track technological trends cannot be dismissed, as digitization, automation, and AI are scaling new heights with their immense power to revolutionize the fashion industry. The future lies in the amalgamation of hand and technology, synergy between both, and combining their strengths to support the environment and boost the economy.

It is heartening to inform you that the NIFT Journal of Fashion is now indexed on DELNET, JGate, EbscoHOST, and Google Scholar. The presence of the journal on reputed indexing platforms augments its credibility, reaching out to a wider academic and research community. I am confident that this volume covering meaningful research on novel approaches, models, and innovations contributes to bridging the gap between handmade and technology and offers valuable insights for fashion professionals, academicians, scholars, and policymakers. As NIFT celebrates its 40th year, the institute continues to be the torchbearer in the world of fashion, paving the way forward towards a sustainable, inclusive, and technology-empowered future.

Tanu Kashyap, IAS
Director General, NIFT

MESSAGE

The fourth volume of the NIFT Journal of Fashion touches upon an important topic of integrating traditional craftsmanship and technology, as their coexistence shall be the driving force to shape a responsible and an upbeat future in the fashion landscape. As we enter an era marked with disruptive AI-driven transformations, the industry is rethinking and reimagining materials, processes, production methods, and consumption practices. While handcrafted traditions resonate with preservation of heritage, the value of hand skills, and artisan livelihoods, technology opens up the potential to achieve speed, precision, and scalability. The confluence of handmade and technology is the way forward that will redefine the very journey of fashion.

This volume brings to light multiple perspectives, advocating sustenance of craft with the support of technology, material and product innovation, and a balanced approach to blend craft and technology in fashion and textile practices as well as design curriculum. The research highlights interdisciplinary approaches and ecosystems that will emerge in the future. I hope the research inspires new possibilities for design and an era of innovation and mindfulness.

I extend my wholehearted appreciation to the Publication unit for yet another enriching volume showcasing scholarly excellence, aligned with NIFT's goal to foster a larger movement that is culturally rooted, sustainable, and harnessing the potential of technology to meet the demands of the creative global industry.

Noopur Anand
Dean (Academics), NIFT

From the Editor's Desk

We are delighted to present the fourth volume of the NIFT Journal of Fashion, which focuses on the fusion of handmade brilliance with progressive technological innovations, the forces that will transform fashion, providing limitless possibilities in the realm of design. The volume brings together research that envisions the seamless integration of heritage and technological advancement, guiding the path towards sustainability, efficiency, and innovation, the need of the hour to strive for a more mindful and responsible future.

Highlighting the role of technology to empower the handloom sector and provide a global competitive edge, *Singh, Joshi, Khazanchi and Kulkarni* point to the importance of authentication and premiumization of Kashmiri handloom products that can be achieved by integrating a range of solutions like QR codes, IoT sensors, AI, ML, and AR within handloom production and post-production supply chains. Further, *Roy, Majumdar* and *Dargan* reiterate the application of technology in the craft economy through a case study on KOSHA, a social-tech solution for authenticity and traceability of handloom products, and its impact on artisan livelihoods and consumer awareness. *Singh, Jana* and *Panghal* develop a manufacturability assessment framework for Fused Deposition Modeling (FDM), which will be useful to assess the suitability of the object to be manufactured by FDM. The framework would be useful to avoid product failure, thus saving on resources, energy, and time. In an endeavor to support children with autism spectrum disorders, *Saikia, Mukherjee* and *Nandi* propose the integration of functional clothing with electronic sensors for a visual and tactile sensory experience, enabling autistic children to cope and adapt to change effectively. *Lal* and *Dhingra* examine sustainable strategies employed by Indian fashion and textile enterprises that range from traditional craft practices and cultural preservation to the application of AI-supported technologies for optimization and efficiency. Rethinking curriculum in today's time, *Reddy, Gopal* and *Kumar* propose the CRAFTECH framework, a holistic and future-oriented model that balances traditional skills with contemporary tech-driven practices. *Chauhan* and *Rana* design and develop a sustainable board game using plastic waste and eco-friendly materials that endeavors to sensitize consumers and foster environmental awareness. Another design innovation by *Lokare* and *Bhatnagar* rejuvenates Paithani weaving by inserting copper wire as weft to enhance the durability and shape retention, making it suitable for structured couture garments. *Parameswaran* conceptualizes an integrated oscilloscope-AI-artisan feedback system and assesses its feasibility as a pathway to improve quality control in handloom production, thus boosting sales and artisan livelihoods. Lastly, *Yadav* and *Jena* propose a conceptual framework based on the UTAUT model to investigate the factors impacting e-commerce adoption among handloom weavers.

We are optimistic that this volume will inspire meaningful dialogue and robust research that connects tradition and technology, celebrating both artisanal wisdom and emerging tech-innovation.

Ruby Kashyap Sood
Editor-in-Chief

Deepak Joshi
Associate Editor

Contents

1. Reviving Kashmiri Handloom: Leveraging Emerging Technologies for Preservation and Premiumization — 1
Vishad Vivek Singh, Sanchita Joshi, Vikrant Khazanchi and Sanish Shirish Kulkarni

2. Heritage Meets Innovation: Elevating Traditional Crafts through Technological Advancements for Sustainability — 21
Satabdi Roy, Gaurav Majumdar and Vikas Dargan

3. Development of Framework for Feasibility Study of Fabrication of Spare Parts Using Fused Deposition Modeling: A Delphi Approach — 36
Abhilasha Singh, Prabir Jana and Deepak Panghal

4. Tactile and Visual Sensory-Based Adaptive Functional Clothing for Children with Autism Spectrum Disorder — 63
Tulika Saikia, Sandip Mukherjee and Dalia Nandi

5. Traditional Wisdom to Artificial Intelligence: Strategies for Sustainable Fashion and Textile Practices in India — 83
Nandini Lal and Sudha Dhingra

6. Balancing Heritage and Innovation: A Study on Traditional Craftsmanship and Technological Integration in Design Curricula — 108
Chiranjeevi Reddy Gudimetla, Priya Darshini Gopal and Rajesh Kumar Gajam

7. Strategic Eco-Play: Rethinking through Sustainable Design — 129
Shivang Chauhan and Anupam Rana

8. Reinventing Paithani Weaving: Integrating Metallic Wire for Enhanced Strength, Durability, and Contemporary Aesthetic Appeal — 145
Neena Lokare and Sneha Bhatnagar

9. A Conceptual Framework Using Oscilloscope–AI Integration for Resonance and Quality Mapping in Handloom Textiles — 162
Deepa Parameswaran

10. Building a Conceptual Framework to Study Factors Influencing E-commerce Adoption by Handloom Weavers — 184
Shubhangi Yadav and Binay Bhusan Jena

11. Profiles of the Members of the Editorial Board — 204

Reviving Kashmiri Handloom: Leveraging Emerging Technologies for Preservation and Premiumization

Vishad Vivek Singh, Sanchita Joshi, Vikrant Khazanchi and Sanish Shirish Kulkarni

Abstract

The existence of the centuries-old traditional Kashmiri handloom industry, particularly Pashmina shawls and carpets, faces a serious threat due to the inundation of markets with cheap, machine-made products. This, coupled with the existence of exploitative middlemen, technology non-upgradation, and other legacy challenges, has led to extremely low wages and penury among the Kashmiri artisans. The seriousness of the situation is reflected in the fact that the younger generation are abandoning centuries-old traditions for more secure alternative livelihoods. With this backdrop, the objective of this article is to elucidate potential emerging technology use cases, which can help revive the production and post-production supply chains of Kashmiri handloom products, specifically Pashmina shawls and Kashmiri carpets. The study is based on qualitative data gathered via focus group discussions, unstructured interviews, and a two-day field immersion workshop conducted with Kashmiri artisans, government officials, and Indian technology startups between December 2022 and June 2023. Findings from the study suggest that the pain points primarily afflicting Kashmiri handloom products pertain to authentication and (re)premiumization and preservation of skills and knowledge of master artisans to ensure perpetuation of the handmade. In this regard, the study suggests that there is scope and a need to systematically integrate a range of emerging technology solutions, such as PUF-based QR codes, IoT sensors, AI and ML technologies, and AR, based on a technology stack approach in Kashmiri Pashmina and carpet supply chains. From a policy perspective, the article emphasizes the need to overcome the 3A challenges—awareness, availability/affordability, and access—to ensure successful technology adoption and trickle-down benefits to Kashmiri artisan communities. The research findings provide guidelines to policymakers, stressing the importance of

building a multi-stakeholder approach, engaging the artisans, government, innovators, and civil society to collaborate for successful integration of technology in handloom production and post-production value chains. Such initiatives shall empower the handloom sector and provide a competitive edge in the global market.

Keywords: Kashmiri handloom, emerging technology, technology adoption, Pashmina, Kashmiri carpets, preservation, premiumization

Introduction

Handloom products are an integral part of India's socio-cultural milieu and economy. The handloom industry in India has evolved tremendously over time, embodying the cultural richness and diversity of its geographic regions as well as the many waves of history that have swept the subcontinent. However, evolution has not been without its challenges. Almost 200 years of British imperialism wrecked the handloom and handicrafts sector, which otherwise was the backbone of India's economy (Kumar et. al., 2021). Even after gaining independence, artisans have continued to struggle with low wages, outdated techniques, and an inundation of markets with cheap machine-made products, which has significant human development implications for over one crore artisans across 2,000 specialized craft clusters in India—including 1,463 handloom clusters and 744 handicraft clusters under the Ambedkar Hastshilp Vikas Yojana (Development Commissioner Handlooms, n.d.; Ministry of Textiles, n.d.). According to the latest estimates, for 66 percent of weaver households, average monthly income from all sources is less than Rs 5,000 (Ministry of Textiles, 2020). Moreover, about 26 percent of the weaver households are Antyodaya (poorest of the poor) card holders, reflecting the abject situation of the artisans associated with the handloom sector (ibid.). However, when juxtaposed with the fact that handloom exports alone were valued at INR 1,446 crore in 2022-23, according to the Development Commissioner Handlooms, n.d.), the artisans' income situation reflects an aberration, necessitating urgent policy interventions.

Within India, the Union Territory of Jammu and Kashmir is especially world-renowned for its ultra-luxury, niche, and high-quality products like Pashmina shawls, particularly Kani, and Kashmiri carpets. The Jammu and Kashmir handloom sector, together with handicrafts, employs around 3.5 lakh artisans, with significant implications for livelihood security and human development. However, despite being the mainstay of the region's economy, the total handicrafts and handloom exports from Jammu and Kashmir have declined sharply from INR 1,643 crore in 2011-12 to INR 635 crore in 2020-21 (AGNIi

Mission, 2023). This downward trend can be attributed to a variety of challenges afflicting the sector. These include the prevalence of exploitative middlemen, credit access, the threat to intergenerational continuation due to lack of interest among the younger generation, lack of brand image, product design and development not in tandem with market demand, competition with machine/power loom-made products, international competition, and inadequacy of appropriate marketing platforms (Government of Jammu and Kashmir, 2020; Majeed and Swalehin, 2020; Ishrat et. al., 2020).

However, the state policymakers (especially the Directorate of Handicrafts and Handloom, Kashmir) are actively instating measures to resolve these pain points and direct efforts towards (re)premiumization and preservation of Kashmiri handloom products. In this regard, a key pillar of their strategy is emerging technology integration in the handloom product supply chain. For example, Jammu and Kashmir is the first Indian union territory to deploy QR-based codes for all its crafts to track product provenance (Sinha, 2023). Such forward-looking initiatives leveraging India's technological capabilities not only help revive and make Kashmiri handloom products relevant in the market but also provide a case for larger integration of technology within India's traditional handloom industries.

At present, Industry 4.0 pervades every aspect of life in the 21st century. It subsumes within it a gamut of emerging technologies such as artificial intelligence (AI), machine learning (ML), the internet of things (IoT), and cyber-physical systems (CPS). It is characterized by technology fusion—the merger of the physical and the digital, with significant implications for both industrial and human development. These technologies, constantly evolving themselves, are finding new and varied use cases and revolutionizing industries (Malik, Muhammad and Waheed, 2024), even for those sectors where technology integration has been a bare minimum. For instance, cottage industries, specifically the centuries-old traditions of handloom weaving, are exemplified by the government of Jammu and Kashmir.

The integration of advanced technology systems such as AI, IoT, and ML can redefine traditional craftsmanship. They can play an instrumental role at almost every node of handloom product supply chains and help enhance productivity, distinguish handmade products from machine-made ones, provide enhanced consumer experience with more effective and interactive articulation of the product narrative and immersive experience, expand reach to global markets, and allow for global knowledge exchange (Aounzou, Kalloubi and Boulaalam, 2022; Zabulis et al., 2022; Halim, Ibrahim and Tawab, 2024). Each of these, in turn, can help hyperlocal artisans reap benefits in terms of livelihood security and fair and higher wages while simultaneously ensuring the intergenerational continuity of their craft.

With this backdrop, the objective of the research is to elaborate on the role that emerging technology solutions can play in the preservation and premiumization of the Kashmiri handloom industry, particularly the Pashmina and carpet supply chains, which also represent a larger adoption use case across India's handloom sector.

Literature Review

The Kashmiri handloom industry, particularly the production and post-production supply chains of high-value Pashmina shawls and carpets, is afflicted with numerous challenges, which threaten its growth and very existence. Majeed and Swalehin (2020) explore deeper the socio-economic conditions and challenges faced by carpet weavers in the Pulwama district of Jammu and Kashmir. The findings suggest that carpet weavers belong to the poorest of the poor households, with conditions further aggravated due to exploitation by middlemen and intermediaries, resulting in lower wages. This highlights that the Kashmiri carpet industry is in the throes of decline, which can be primarily attributed to unsustainable competition from machine-made products and rapidly changing consumer preferences. These challenges have resulted in a reluctance from younger generations to continue to associate themselves with the craft. Meanwhile, Ishrat et al. (2020) analyze various issues afflicting the Kashmir handloom industry, with special reference to the supply chain of cashmere (pashmina). The key issues identified include a high level of supply chain fragmentation with repercussions for efficiency and quality; a decline in traditional skills among the younger generation due to the increasing non-lucrativeness of the industry; and the middlemen trap, an impediment for artisans to directly access markets and consumers, which also erodes profit share. Moreover, limited technology and innovation adoption is highlighted as an important concern, as it makes the handloom sector lose out in the competition against machine-made products. Similarly, Kumar et al. (2021) elaborate on the evolution of the overall Indian handloom industry and point out that it requires technological advancements and innovation-driven reforms to ensure competitiveness in the global economy.

Hence, it becomes important to assess the role emerging technology can and is playing in the handloom industry. In this context, literature highlights the role of artificial intelligence (AI) in revolutionizing the handloom sector. AI can be utilized in handloom product supply chains to optimize designs, improve quality control, and streamline production. According to Jennifer et al. (2024), AI-driven systems can help automate defect detection in fabrics, where machine learning (ML) algorithms identify woven fabric imperfections, reducing the scope of human error and ensuring consistency. Similarly, computer-based vision systems have been implemented to ensure textile quality control, offering automated solutions to detect problems pertaining to broken yarns and color variations. According to Sabeenian, Paramasivam and Dinesh, (2012), such systems can provide high accuracy and help ensure that handwoven products meet high-quality standards. In simulations conducted by the authors, the system achieved a 96.6 percent accuracy in detecting defects in silk fabrics. Halim, Ibrahim and Tawab (2024) further substantiate that AI can play an instrumental role in small heritage industries by way of improved design quality, reduced production times, and creation of new applications for traditional crafts, such as furnishings and accessories. They further highlight that AI adoption can help revitalize textile arts and crafts and boost their socio-economic contributions, providing a sustainable way forward in present-day's rapidly evolving markets.

In addition to AI, the Internet of Things (IoT) can play a significant role in modernizing traditional handloom operations. IoT-enabled devices, such as sensors and RFID tags, can be used to track loom performance, monitor worker efficiency, and manage energy consumption. In this context, Ingavale et al. (2024) describe an IoT-based system for automating power looms, which minimizes power wastage and records worker performance. IoT integration helps bridge the chasm between traditional craftsmanship and modern operational efficiency, allowing real-time monitoring and control without compromising the nuances of the manual weaving process. Moreover, deep learning approaches have been developed to authenticate traditional handloom textiles from counterfeit powerloom imitations. Das et al. (2024) introduced a Deep Metric Learning (DML) model that achieved 97.8 percent accuracy in distinguishing genuine handloom fabrics from their powerloom counterparts. Further, as noted by Jennifer et al. (2024), AI integration with handloom product supply chains can help predict demand fluctuations, optimize inventory management and logistics, and facilitate the efficient management of production cycles, which are aligned with real-time market needs.

Meanwhile, Jamaludin et al. (2023) highlight the role of mobile applications in enhancing real-time interaction and digital marketing for artisans, allowing them to expand market reach. Notably, augmented reality (AR) applications can enable users to digitally visualize traditional motifs, thereby promoting both cultural preservation and consumer engagement.

While there exists a gamut of technologies, which can help reimagine and redefine how handloom products are actually made and perceived by consumers, significant adoption challenges exist. As noted by Jennifer et al. (2024), training and upskilling of artisans to use emerging technologies is often overlooked. As such, artisans are unable to leverage the benefits of AI and IoT innovations. This calls attention to the need to prioritize capacity building and accessibility. Meanwhile, Bortamuly and Goswami (2015) suggest that education, income levels, and access to government support play a critical role in the adoption of technology. For instance, industry owners with higher levels of education and income are more likely to adopt modern technologies, while smaller owners often lack the resources or knowledge to seamlessly make a transition.

Thus, the main takeaway from the literature review is that while emerging technologies can complement the 'hand' and help transform the handloom product supply chains, there is a need for policymakers to take cognizance of the adoption challenges and put in place requisite interventions, lending a 'helping hand' to overcome the same.

Methodology

The research is based on primary data (supplemented with secondary data) conducted by the authors as part of the Government of India's AGNIi Mission program setup under the aegis of the Office of the Principal Scientific Adviser and Invest India. The research was undertaken in close collaboration with the Directorate of Handicrafts and Handloom, Kashmir, in the handicrafts and handloom clusters of Srinagar, Jammu and Kashmir. The field visits were conducted during December 2022 and June 2023. The authors conducted a series of Focus Group Discussions (FGDs) and unstructured interviews with Kashmiri artisans engaged with making carpets and Pashmina shawls in the clusters of Narwara, Kathi Darwaza, Zadibal, and Bagh Ali Mardan Khan, in Srinagar; along with senior officials from the Directorate of Handicrafts and Handloom, Kashmir, and its allied agencies, namely the School of Design, Craft Development Institute, Indian Institute of Carpet Technology, UNDP's (Handloom Project) facility, and the Pashmina Testing Facility; and select Indian emerging technology startups.

The methodology was executed in three broad parts (Table 1):

First, in December 2022, the authors undertook a field visit and conducted FGDs and unstructured interviews with Pashmina shawl and carpet artisans and government officials to surface pain points. With regard to the FGDs, the organizing principle was the handloom product supply chain with which the artisans engaged, and the objective was to identify pain points in the production and post-production supply chains, especially with respect to tools, designs, and market access. As such, three FGDs (with 8 participants in each) were conducted: one with weavers associated with carpets, another with Pashmina shawl weavers, and a third with artisans engaged with embroidery (Sozni) on Pashmina shawls. It is to be noted that Sozni embroidery is an important post-loom process and constitutes an important value addition to the final product. It consists of back-breaking manual work, which is in direct competition with machine-made embroidery. With regard to the participants' demographics, for the two FGDs with carpet and Pashmina weavers, participants were largely male in the age group of 30-50 years; however, the embroiderers' group comprised young women in the age group of 20-25 years. This hints at the gendered work distribution in the Kashmiri handloom product supply chains wherein women are largely engaged in non-loom but highly value-added activities. Additionally, unstructured interviews were used for interactions with master artisans (five) and government officials (thirty). The objective was to better understand the legacy practices, the evolution of Kashmiri Pashmina shawls and carpets over time, and the existing policies and programmatic interventions in place.

Second, based on the pain points identified during the field visit in December 2022, the authors subsequently (between January and April 2023) identified nine Indian emerging technology startups and government research institutions (Table 1). The objective was to better understand the scope and possibility of emerging technology integration in the supply chain of Pashmina shawls and carpets.

Third, in June 2023, a two-day Field Immersion Workshop was conducted in Srinagar to bring together the artisans and representatives from startups and government research institutions. The objective was to better understand the integration of emerging technologies in the supply chain of Pashmina shawls and Kashmiri carpets in terms of operational scenarios and technical functional requirements. These interactions were free-flowing discussions between the artisans and representatives from startups and government research institutions mediated by the authors. The Immersion Workshop included 10 artisans (five Pashmina weavers and five carpet weavers), two representatives each from six Indian technology startups, and government research institutions (Table 1). The workshop was structured as a problem-solution matching exercise, wherein the artisans demonstrated the pain points, and representatives from startups and research institutions deliberated on existing or probable emerging technology interventions.

Thus, a well-grounded methodology was adopted to both understand pain points and identify the scope of emerging technology interventions.

Table 1: Overview of objectives, methods, and participants

S.No.	Objectives	Methodology	Participant Details
1.	Pain-point identification	FGDs *(Each was conducted at the location of work)*	Three FGDs: 1. Pashmina shawl weavers (8 participants, 30–50 years, males) 2. Carpet weavers (8 participants, 30–50-years, males) 3. Sozni embroiderers (8 participants, 20–25-years, females)
		Unstructured interviews	1. 5 Master artisans 2. 30 Government officials • 10 Officials: Directorate of Handicrafts and Handloom, Kashmir • 8 Experts: Craft Museum (School of Designs), Srinagar • 7 Domain Experts: Indian Institute of Carpet Technology, Srinagar • 5 Officials: UNDP's (Handloom Project) facility
2.	Scope of integrating emerging technology solutions	Free-flowing discussions	9 Indian emerging technology startups related to mixed reality, AI, IoT, and provenance tracking Government research institutions: Bombay Textile Research Institute, Wool Research Association, and RuTAG Centres of IIT Madras and Roorkee
3.	Understanding emerging technology integration with regards to field operational scenarios and actual technology functional requirements	Two-day field immersion workshop in Srinagar (included visits to Craft Museum (School of Designs), Indian Institute of Carpet	10 artisans (5 Pashmina shawl weavers and 5 carpet weavers) 2 representatives each from six Indian emerging technology startups related to mixed reality, AI, IoT, and provenance tracking

S.No.	Objectives	Methodology	Participant Details
		Technology, Craft Development Institute, Wool Processing Unit, dyeing clusters, Pashmina testing facility, Pashmina weaving centres, carpet weaving clusters, and export houses) Free-flowing discussions	2 representatives each from government research institutions (Bombay Textile Research Institute, Wool Research Association, and RuTAG Centres of IIT Madras and Roorkee)

Source: Authors' compilation

Integration of Emerging Technologies with Kashmiri Handloom Products

It emerged during the FGDs and interviews that the easy availability of cheap counterfeit machine-made products has had the most adverse impact on the Kashmiri handloom industry, with various second-order challenges that have severe implications for artisans' livelihoods and the continuity of the handmade itself.

The emerging technology innovations provide significant opportunities to revive the traditional Kashmiri handloom industry with significant benefits for artisans and help to preserve Kashmir's centuries-old rich handloom heritage, which otherwise runs the peril of languishment (Ishrat et al., 2020). A systematic approach is required to integrate technology with Kashmir's handloom industry with a focus on addressing two broad problem statements that encompass different supply chain nodes: (a) authentication and (re)premiumization of Kashmiri handloom products and (b) preservation of skills and knowledge of Kashmiri master artisans for intergenerational transfer to ensure the perpetuation of the handmade. These problem statements were identified on the basis of interactions with artisans and officials during the FGDs, interviews, and the field immersion workshop. Table 2 describes a select overview of qualitative insights that emerged from the discussions and their alignment with the problem statements.

Table 2: Select qualitative insights

S.No.	Problem Statement	Qualitative Insights
1.	Authentication and (re)premiumization of Kashmiri handloom products	**Lack of traceability and control on product labelling:** "After we sell the shawl, we don't know where it goes or how is it labelled." (FGD – Pashmina weavers) **Loss of value due to competition from machine-made products:** "Machine-made products are similar. Customers don't know the difference and bargain even when buying original Kani or Sozni embroidery products. This has also significantly brought down wages." (FGD – Embroidery artisans) **Lack of technology awareness**: "We have never heard of IoT or AI." (FGD – Carpet weavers) **Desire for technology adoption:** "If I can scan a code that shows this is my shawl, how I made it, then the buyer will trust and be ready to pay the price. This is something we need, something that can prove our work." (Pashmina weaver, Field Immersion Workshop) **Multiplicity of government interventions and lack of awareness:** "Government has launched QR codes and hologram tags, but their multiplicity has confused artisans and some in remote regions are not even aware." (Government official, interview) **Emerging technology solution for authentication:** "Our IoT device can be placed on the loom without requiring any alterations. It tracks weaving real-time and provides each shawl with a digital footprint." (IoT startup, Field Immersion Workshop)
2.	Preservation of skills and knowledge of Kashmiri master artisans for intergenerational transfer to ensure the perpetuation of the handmade	**Physical vulnerability of traditional Taleem designs:** "All my Taleems are handwritten and old. If they tear or get wet, the design is lost forever." (Master carpet weaver, interview) **Intergenerational skill transmission:** "My son doesn't know how to read the Taleem. He says it is difficult. He wishes if he could use a phone or computer to learn faster." (FGD – Carpet weaver)

S.No.	Problem Statement	Qualitative Insights
		Lack of systematic preservation: "Taleems are largely lying in the homes of artisans. One more flood like 2014 and they will be gone forever." (FGD – Carpet weaver) **Emerging technology solution for preservation:** "Our OCR can read Taleem scripts. We can build tools to digitise the designs so that they are never lost." (AI startup, Field Immersion Workshop) **Desire for technology adoption:** "If this AI tool can read Taleems and turn them digital, even my grandchildren will be able to read and our craft will be saved." (FGD – Carpet weaver) **Saving the handmade:** "We need digital repositories where artisans can archive designs, document processes, and connect with national and international artisans and design houses to include global market trends." (Craft Museum, School of Designs official, interview)

Source: Authors' compilation from primary data collected between December 2022 – June 2023

In this context, the following sub-sections elaborate on emerging technology use cases for (re)premiumization, preservation, and propagation within the Kashmiri handloom industry based on pain points identified via qualitative unstructured interviews and focus group discussions with both local Kashmiri artisans and senior officials at the Directorate of Handicrafts and Handloom, Kashmir.

Authentication and (re)premiumization of Kashmiri handloom through emerging technology integration

With regard to premiumization, the pivotal issue faced by Kashmiri artisans pertains to the inability of consumers to authenticate handmade Kashmiri products in the market. Markets are flooded with mass-produced machine-made/power loom imitations, especially from surrounding industrial regions of Amritsar and Ludhiana, which are often passed off as genuine Kashmiri handloom. Moreover, the introduction of multiple labels—plastic, hologram, and fabric-based tags for Geographic Indication (GI) and non-GI products—has created further confusion for consumers about product authenticity. The repercussions of this situation have primarily been two-fold: a devaluation of true craftsmanship and a significant decline in artisan wages, with some artisans today earning as little as Rs. 200 per day.

Further, while Kashmiri handloom products like Pashmina and carpets are meant and designed for niche luxury markets, there is little awareness among consumers about their distinguishing features, with implications on market demand. For example, authentic Kashmiri Pashmina with fibers measuring 12-13 microns (Shakyawar et al., 2013) is more premium than cashmere, measuring 12-20 microns (as corroborated during FGDs and interviews); however, due to lack of consumer awareness, the former is unable to capture and leverage the gains in global luxury handloom markets, with a major consequence for Kashmiri artisans.

Last but not least, Kashmiri handloom markets are characterized by the pervasiveness of middlemen, which further erodes the artisan earnings. As surfaced during FGDs, artisans mostly rely on middlemen (most times large exporters) for market access and branding, who typically control the marketing narrative and mostly marginalize artisans with just a meager share of the products' final price.

Considering the above-identified issues, a range of emerging technology interventions can be utilized in a 'stack approach' to help resolve the pain points. In the Information Technology (IT) sector, the technology stack approach refers to the systematic selection and integration of various technologies, for instance, programming languages, database management systems, operating systems, and frameworks, to develop effective solutions for complex problems (Nikulchev, Ilin and Gusev, 2021). A similar approach can be extended to real-world challenges by leveraging a combination of technologies. This would entail breaking down a larger problem statement into smaller components, and each technology in the stack can address a specific aspect of the problem, ultimately leading to a comprehensive and efficient solution.

In this regard, a key identified solution pertains to the usage of Physically Unclonable Function (PUF) QR codes, which provide a digital fingerprint for each unique product, allowing to check for and establish authenticity. PUF-based QR codes make use of unique, unclonable physical properties that arise from random variations during the manufacturing process, making them highly secure and resistant to counterfeiting. The authors' conversation with an Indian startup that offers PUF-based QR codes as products brought to light that unlike traditional QR codes, which can be easily replicated, PUF-based QR codes embed these random physical variations, providing a unique identifier that cannot be cloned or tampered with. Their usage helps certify that a handloom product is genuinely handmade and simultaneously allows consumers to trace its entire production journey—from raw material sourcing to the final finished product. For instance, consumers can instantly scan PUF QR codes on, say, a Kani Pashmina shawl or a Kashmiri carpet to learn about the artisan involved in making the piece, the knot count, weaving techniques, etc., establishing authenticity, premium quality, and a direct connection between the buyer and the weaver, significantly increasing the chances of purchase.

In addition to PUF QR codes, IoT sensors can be deployed on handlooms to capture real-time motion data during the weaving process. These sensors have the capabilities to track the subtle hand movements of the artisans involved in handloom weaving, making it possible to differentiate between handmade and machine-made products. The data captured via these IoT sensors can be stored and analyzed to provide verifiable proof that a Kashmiri handloom item was woven by hand, rather than on a power loom. Additionally, machine learning-based optical scanners can be introduced to further enhance product verification by detecting the number of knots per inch in carpets and shawls. These scanners, combined with QR code technology, help consumers get a comprehensive understanding of a product's specifications, further establishing product authenticity and uniqueness.

It is important to note that the above-mentioned technological interventions do not simply authenticate and establish the distinctness of Kashmiri handloom products; they can also be used to further enhance consumer experience by allowing artisans and producers to present the consumers with the productive narrative. In this regard, technologies of narrative, such as augmented reality (AR) and interactive displays, can be integrated with the marketing process, offering consumers a visually rich experience, which explains the cultural and historical significance of products.

Digital preservation of Kashmiri handloom heritage

Another major problem identified during the FGDs and qualitative interviews, as also elaborated upon by Ishrat et al. (2020), concerns the lack of preservation of skills and knowledge of Kashmiri master artisans. Most Kashmiri master artisans are aging and nearing the end of their careers, and there is almost no one to take their place. Hence, it becomes imperative to document and preserve their expertise and techniques before they are lost to time. This is especially a pressing concern in the case of Taleems. According to Majeed and Swalehin (2020), Taleems, a unique feature of Kashmir, are coded design instructions used by carpet weavers in the region. These are centuries-old 'handwritten algorithms,' written on fragile sheets of paper, which aid the hand on the loom. Taleems convey important information like thread colors, knots per square inch, and weft lines, and they help artisans create unique Kashmiri carpet designs.

However, handwritten paper repositories of Taleems run the risk of degeneration over time. This can be attributed to both the fragility of the medium and natural calamities like the 2014 floods, which led to the loss of countless unique designs (Khan, 2023), as also stated during the FGDs and interviews, necessitating interventions for preservation. While concerned authorities in Kashmir have undertaken measures to initiate Taleem digitization, the conventional process is slow and entails manual transcription of Taleem symbols into software, which slows down production and jeopardizes the preservation of traditional weaving techniques.

In this regard, an innovative emerging technology solution, which utilizes AI and ML, can be significantly useful. An AI-based solution, enabled by Optical Character Recognition (OCR) technology, powered by Convolutional Neural Networks and Long Short-Term Memory architectures, can help expedite and automate the digitization of Taleems more accurately. These advanced computer vision systems scan the physical Taleems and convert them into digital formats, aiding preservation and creation of a digital design repository. Additionally, customized machine learning algorithms can be developed to extract designs from images and generate new Taleems, offering to both preserve and innovate upon traditional patterns.

Various benefits can be reaped from the adoption of these technological interventions. The use of AI-driven OCR technology enhances the efficiency of the weaving process, as it significantly reduces the time required for digitization. This allows artisans to focus more on the craft while ensuring the integrity of traditional designs. Furthermore, accurate digitization of Taleems helps safeguard centuries-old designs and techniques, preserving them for future generations and ensuring the continuity of the region's cultural legacy. Creation of digital design repositories via the use of emerging technologies can help empower artisans, as they acquire access to innumerable traditional and contemporary design patterns, which can be modified and adapted as per the demands of modern consumers and markets.

With regard to digitization, another area of intervention should focus on building a digital global knowledge exchange platform, which allows artisans to access best practices and designs from around the world. The platform can function as a digital design bank, where artisans can browse, contribute to, and learn from a wide array of designs that reflect both traditional craftsmanship and modern market trends. By fostering a global dialogue around design and craft, such a platform will not only enrich artisan knowledge but also present fresh opportunities for collaboration and market expansion.

Last but not least, an emerging technology intervention, which can help place traditional Kashmiri handloom products in global markets, is the introduction of digital infotainment technologies. These include interactive museum displays, augmented reality exhibits, and virtual reality tours, which can help create an engaging and educational experience for national and international tourists visiting Jammu and Kashmir. It is important to note that tourist footfall in Jammu and Kashmir has been significant in recent years, and officially it stood at approximately 2.1 crore during 2023 that further rose to 2.3 crore in 2024 (India Brand Equity Foundation, 2025). These digital interventions will enable museums to serve as a cultural landmark as well as a learning platform, where students, artisans, and tourists can explore the rich history of Kashmiri handlooms and handicrafts, with implications for translating into purchases.

Conclusion

Industry 4.0 solutions can have far-reaching positive implications on every node of the supply chain for Kashmiri handloom products. Be it design, production, marketing, or distribution, they can redefine the contours of craftsmanship and help Kashmiri cultural heritage adapt to the needs of the 21st century's fashion market demands. In this context, the present paper elaborates on various avenues for integrating emerging technology solutions within Kashmiri handloom product supply chains. Emerging technologies such as PUF-based QR codes, IoT sensors, AI and ML technologies, and AR can help build a niche narrative for Kashmiri handloom products and completely transform their perception among national and international consumers with both micro- and macroeconomic implications.

From a policy perspective, the identified emerging technology use cases for Kashmiri handloom products discussed in this article can be emulated and scaled across India's 1,463 handloom clusters (Development Commissioner Handlooms, n.d.), with the caveat that technology complements the 'hand' and does not substitute it. Policymakers need to intelligently and effectively leverage emerging technology solutions to serve as a conduit between the hyperlocal artisans and global markets. These initiatives can help drive a wider technology-enabled transformation with multiplier effects for approximately 32 lakh handloom workers (Ministry of Textiles, 2020) in terms of livelihood security and varied parameters of human development, with downstream benefits for the Indian economy at large.

However, successful technology integration to leverage tangible benefits would be contingent on overcoming the 3A challenges—awareness, availability/affordability, and access—which impede technology adoption, a not-so-straightforward process. The 3A challenges, which require immediate policy attention, include the following:

- Awareness: Technology adoption is a function of the perceived attributes of innovation, namely, relative advantage, compatibility, complexity, trialability, and observability (Rogers, 1962), which might not always be apparent to adopters, especially rural adopter communities characterized by low levels of education and awareness. The genesis of the same is information asymmetries between adopters (handloom artisan communities in this case) and innovators about the various purposes the innovation can serve and its inherent advantages. Hence, the first step towards successful adoption is to educate artisan communities about the potential technology use cases in the handloom product supply chains. In this context, the government and civil society should create avenues like immersion workshops (as organized and conducted by the authors) to break silos and facilitate dialogue between innovators and artisans. Such an effort would facilitate a bilateral flow of innovation, enabling adoption. Additionally, it will help improve existing innovations and allow for new use-case discovery.
- Availability/Affordability: Even if the artisans are aware of the benefits technology integration can bring, resource constraint is a reality. As highlighted earlier, Indian artisan communities are characterized by low levels of income. However, emerging technology solutions usually entail high device costs as well as additional costs for any infrastructure requirements, significantly impeding adoption. Resolving such problems would require governments to become 'procurers of first resort.' Leveraging emerging technology solutions via government procurement mechanisms will help build an effective foundation to scale technology adoption among artisans of the region. The procured solutions can be provided to artisans at subsidized rates or made available for usage with a minor fee at government Common Facility Centers in handloom clusters.
- Access: The third facet of the problem is that handloom artisan communities are characterized by low levels of education. According to the Ministry of Textiles (2020), nearly 1 in 4 weavers have not received any form of formal education. Moreover, 14 percent have not completed primary-level education. This poses digital literacy barriers, wherein availability of technology does not guarantee usage and will have to be complemented with requisite skilling to

help unleash the potential of emerging technologies (Majumdar, Basu and Jain, 2021). Hence, policy mechanisms for the digital empowerment of artisans become imperative. With governments taking the first step, this would have to involve participation of civil society as well as big export houses, which can provide required access to artisan communities and help undertake organized skilling initiatives.

Thus, calibrated technology integration within handloom production and post-production value chains is a sine qua non to make our handloom sector globally competitive. However, this requires policymakers to adopt a multi-stakeholder approach, which brings together government, artisans, and innovators as well as civil society to overcome the 3A challenges, which deter successful technology adoption.

Acknowledgement

The guidance from the Office of Principal Scientific Adviser (PSA) to the Government of India and the support from the Directorate of Handicrafts and Handloom Kashmir, Government of Jammu and Kashmir, have been instrumental to the success of the study. We gratefully acknowledge the support and inputs from Dr. Suruchi Mittar and Sanid Patil from Invest India, as well as former AGNIi Mission Head Rahul Nayar.

References

AGNIi Mission, 2023. *Innovation for Handicrafts and Handloom Cluster 1.*Office of the Principal Scientific Adviser to the Government of India, [online] Available at: <https://psa.gov.in/CMS/web/sites/default/files/publication/Innovation%20for%20Handicrafts%20%20and%20Handloom%20Cluster1.pdf> [Accessed 18 August 2025].

Aounzou, Y., Kalloubi, F., and Boulaalam, A., 2022. Toward an IoT-based system to ensure product identification of Moroccan handicrafts. In: S. Motahhir and B. Bossoufi, eds. *Digital technologies and applications. ICDTA 2022.* Lecture Notes in Networks and Systems, Cham: Springer. https://doi.org/10.1007/978-3-031-02447-4_29.

Bortamuly, A.B. and Goswami, K., 2015. Determinants of the adoption of modern technology in the handloom industry in Assam. *Technological Forecasting & Social Change* [e-journal] 96, pp.31-43. https://doi.org/10.1016/j.techfore.2014.04.018.

Das, A., Deka, A., Medhi, K. and Saikia, M.J., 2024. Deep learning to authenticate traditional handloom textiles. *Information,*[e-journal] 15(8), pp.465.https://doi.org/10.3390/info15080465.

Development Commissioner Handlooms, n.d. *Handloom Exports – 10 Years Data by HS Code*. [pdf] <https://handlooms.nic.in/assets/img/Statistics/HS%20code%2010%20yrs%20data.pdf>[Accessed 15 June 2025].

Development Commissioner Handlooms, n.d. *List of Handloom Clusters under AHVY*. [online] Available at: <https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fhandlooms.nic.in%2Fassets%2Fimg%2FHandloom%2520Clusters%2F2500.xlsx>[Accessed15 June 2025].

Government of Jammu and Kashmir, Industries and Commerce Department, n.d. *Jammu and Kashmir Wool Processing, Handloom, Handicrafts Policy - 2020*. [pdf] Available at:<https://jkindustriescommerce.nic.in/Orders%202020/54%20IND%20of%202020.pdf> [Accessed 28 September 2024].

Government of Jammu and Kashmir, 2020. *Order No. 54-IND of 2020: Recognition of Traditional Industries*. [pdf] Available at: <https://industriescommerce.jk.gov.in/Orders%202020/54%20IND%20of%202020.pdf> [Accessed 15 June 2025]

Halim, M.S.A., Ibrahim, G.E. and Tawab, F.M.A., 2024. Utilizing artificial intelligence techniques to develop some textile craft industries. *International Design Journal,* 14(5), pp.43-63. [online] Available at:<https://idj.journals.ekb.eg/article_372636.html> [Accessed 24 September 2024].

India Brand Equity Foundation, 2025. *About Jammu and Kashmir: Information on Tourism, Industries, Economy & Geography*. [online] Available at: <https://www.ibef.org/states/jammu-kashmir> [Accessed 19 August 2025].

Ingavale, S.U., Gujale, V.K., Karande, V.R., Katkar, A.S. and Patil, M.D., 2024. IoT-based automation of power loom in textile industries. [pdf] *International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET),*Available at:<https://www.ijmrset.com/upload/46_IoT.pdf> [Accessed 20 September 2024].

Ishrat, S.I., Grigg, N.P., Bezuidenhout, C.N. and Jayamaha, N.P., 2020. Sustainability issues in the traditional cashmere supply chain: Empirical evidence from Kashmir, India. *Sustainability,* [e-journal] 12(24), p.10359. https://doi.org/10.3390/su122410359.

Jamaludin, N.S.A., Othman, A.N., Albakry, N.S. and Yusoff, M.D.M., 2023. *The contribution and potential of digital transformation on Malaysian handicraft products.* [pdf] GSE e-journal of education. Available at: https://weedutech.com/journal/gse/toc/2023/2.pdf [Accessed 25 August 2025].

Jennifer, K.C., Indu, G.K., Hayavadana, J., Kulkarni, S.R., Srinivasulu, K., Kapoor, V., Priyadharshini, S.N. and Umamageshwari, S.,2024. *Application of artificial intelligence (AI) in the handloom industry*. [pdf] African Journal of Biological Sciences. Available at:<https://www.afjbs.com/uploads/paper/ef192e14ebcc64a6257c54678705d0e6.pdf> [Accessed 24 September 2024].

Khan, A.A., 2023. *Kashmir floods 2014: recovery to resilience.* National Institute of Disaster Management, Ministry of Home Affairs, New Delhi: India.

Kumar, V., Kumari, P., Yadav, P. and Kumar, M., 2021. Ancient to contemporary — The saga of Indian handloom sector. *Indian Journal of Fibre & Textile Research,* [e-journal] 46(4). https://doi.org/10.56042/ijftr.v46i4.59209.

Majeed, I. and Swalehin, M., 2020. Carpet weaving occupation in Kashmir: An analysis of socio-economic conditions of carpet weavers of Pulwama District. *Asian Journal of Economics, Business and Accounting,* [e-journal] 16(1), pp.41-49. https://doi.org/10.9734/AJEBA/2020/v16i130230.

Majumdar, B., Basu, S. and Jain, S., 2021. *Digital empowerment and Indian handlooms: Case-based policy recommendations.* [pdf] Economic and Political Weekly. Available at:<https://www.defindia.

org/wp-content/uploads/2021/04/Digital-Empowerment-and-Indian-Handlooms.pdf> [Accessed 19 September 2024].

Malik, S., Muhammad, K. and Waheed, Y., 2024. Artificial intelligence and industrial applications: A revolution in modern industries. *Ain Shams Engineering Journal,*[online] Available at:<https://www.researchgate.net/publication/381160287_Artificial_intelligence_and_industrial_applications-A_revolution_in_modern_industries> [Accessed 20 September 2024].

Ministry of Textiles, Fourth All India Handloom Census. *Office of the Development Commissioner for Handlooms, Ministry of Textiles, Government of India,* 2020. Available at: https://handlooms.nic.in/assets/img/Statistics/3736.pdf [Accessed 21 Sept. 2024].

Ministry of Textiles, n.d. *Directory of Handicraft Clusters under AHVY*. Available at: <http://www.craftclustersofindia.in/site/Cluster_Directory.aspx?mu_id=3> [Accessed15 June, 2025].

Nikulchev, E., Ilin, D. and Gusev, A., 2021. Technology stack selection model for software design of digital platforms. *Mathematics,* [e-journal] 9(4), p.308. https://doi.org/10.3390/math9040308.

Rogers, E.M., 1962. *Diffusion of Innovations,* 3rd ed. New York: The Free Press.

Sabeenian, R.S., Paramasivam, M.E. and Dinesh, P.M., 2012. Computer vision-based defect detection and identification in handloom silk fabrics. *International Journal of Computer Applications,* [online] Available at:<https://www.researchgate.net/publication/230750503_Computer_Vision_Based_Defect_Detection_and_Identification_in_Handloom_Silk_Fabrics> [Accessed 22 September 2024].

Shakyawar, D.B., Raja, A.S.M., Kumar, A., Pareek, P.K. and Wani, S.A., 2013. Pashmina fibre — Production, characteristics and utilization. *Indian Journal of Fibre & Textile Research,*[online] Available at:<https://www.researchgate.net/publication/265016291_Pashmina_fibre-Production_characteristics_utilisation> [Accessed 19 September 2024].

Sinha, M., 2023. LG launches QR code-based labels of 13 GI and non-GI registered crafts in J&K. *Economic Times*. [online] 29 January. Available at: <https://www.business-standard.com/article/current-affairs/lg-launches-qr-code-based-labels-of-13-gi-and-non-gi-registered-crafts-in-j-k-123012900681_1.html>[Accessed 15 June 2025].

Zabulis, X., Meghini, C., Dubois, A., Doulgeraki, P., Partarakis, N., Adami, I., Karuzaki, E., Carre, A-L., Patsiouras, N., Kaplanidi, D., Metilli, D., Bartalesi, V., Ringas, C., Tasiopoulou, E. and Stefanidi, Z., 2022. Digitisation of traditional craft processes. *Journal on Computing and Cultural Heritage (JOCCH),*[e-journal] 15(3), pp.1-24.https://doi.org/10.1145/3494675.

About the authors

Vishad Vivek Singh is Assistant Manager at Invest India, specializing in emerging technologies and innovation management. He holds a BTech from Delhi Technological University and is currently a part of the Technology & Innovation Division at Invest India. Previously, Vishad was involved with the AGNIi Mission, a part of the Prime Minister's Science, Technology, and Innovation Advisory Council, where he focused on mapping and developing technology stacks to address national-level challenges. His expertise includes identifying advanced solutions for tackling climate change, enhancing training and perimeter security for internal security forces, and emerging innovations for MSMEs, particularly in the handicrafts sector. Currently, Vishad is exploring India's capabilities across strategic technological sectors, with a specific emphasis on quantum technologies.

vishad.singh@investindia.org.in

Sanchita Joshi holds a PhD in Management from the Faculty of Management Studies, University of Delhi, and her research delves into gender disparities in time use, time poverty, and work participation in India. Previously, she was engaged as a consultant with the AGNIi Mission, Office of the Principal Scientific Adviser, Government of India, at Invest India, and has teaching experience at Delhi Technological University and the University of Delhi. Her research interests encompass gender, labor, technology, human development, climate change, and livelihoods.

sanchitajoshi03@gmail.com

Vikrant Khazanchi heads the Technology & Innovation focus at Invest India. In this role, he partners with collaborators from the Indian and the global innovation ecosystems to position India's R&D and technology capabilities in emerging and frontier sectors like quantum, AI, advanced materials, etc., for catalyzing investments in these domains. Previously, he was heading the AGNIi Mission under the Prime Minister's Science, Technology, and Innovation Advisory Council (PM-STIAC), where he formulated technology advice in national priority areas of national security, climate change, and human development for several government agencies. Prior to his work with the Government of India, Vikrant was based out of New York and has extensively worked in the fields of artificial intelligence, product development, and data science. He holds a bachelor's in technology from IIT Delhi.

vikrant.khazanchi@investindia.org.in

Sanish Shirish Kulkarni leads the Indo-Pacific Economic Framework (IPEF)'s Clean Economy engagements at Invest India. As a part of the Global Partnerships & Net Zero team at Invest India, Sanish focuses on leveraging multilateral organizations and plurilateral platforms for catalyzing investments in India's clean economy sectors. He focuses on building sustainable partnerships with diverse stakeholders, including governments, investors, project proponents, climate tech startups, etc. He has led the Human Development vertical at the AGNIi Mission, a program of the Office of the Principal Scientific Adviser to the Government of India. He has focused on the intersection of impact and technology, which could propel human-centered sectors like climate change as well as handicrafts and handlooms.

sanish.kulkarni@investindia.org.in

Heritage Meets Innovation: Elevating Traditional Crafts through Technological Advancements for Sustainability

Satabdi Roy, Gaurav Majumdar and Vikas Dargan

Abstract

India has had a history of culturally rich handloom and traditional craft. Despite the historical and economical vibrancy, the sector today faces multiple challenges. Issues like market fragmentation, policy gaps, and the rise of counterfeit products are rampant. The rise of mechanized, low-cost imitations in both domestic and international markets has weakened consumer trust. This misrepresentation, along with reduced artisan visibility and producers' limited ability to differentiate their work, has in its stead also forced economic marginalization of skilled craftspeople. In an ever-increasing competitive world, the wound cuts deep.

This study explores the role of technological innovation in addressing these long-standing issues through a focused case study of KOSHA, a social-tech enterprise developing authentication and traceability solutions for the craft economy. Adopting a qualitative case study methodology, the research draws upon field observations, structured and semi-structured interviews, and real-time documentation of technology deployment. Data was collected from artisan clusters using KOSHA systems, as well as from program implementers and support organizations. The study foregrounds artisan perspectives, with a particular emphasis on how technology influences their workflows, market access, pricing power, and recognition.

Findings indicate that KOSHA's systems have had a significant impact on both artisan livelihoods and consumer perception. The ability to verify handmade authenticity in real-time through IoT and blockchain-based systems has not only strengthened artisan credibility but also enabled higher price realization in premium markets. In parallel, the use of personalized, media-rich content linked to tamper-proof digital labels has created new pathways for brands and retailers to build trust and emotionally resonate with buyers. Artisans report increased income stability, greater market visibility, and an enhanced sense of dignity tied to the visibility of their names, stories, and creative labor.

This article contributes to existing literature by offering an artisan-centric perspective on digital transformation in the cultural economy, an area often overlooked in broader discussions of fashion tech and supply chain innovation. It argues that technology, when ethically and thoughtfully integrated, can reinforce rather than replace traditional systems of knowledge, production, and identity.

Keywords: Traditional craftsmanship, authentication, supply chain management, sustainable fashion, ethical consumerism, cultural preservation, fashion innovation

Introduction

India's handloom sector, often described as the soul of the country's textile heritage, represents one of the world's oldest and most enduring economic systems. With origins dating back to the Indus Valley Civilization, handloom weaving has long served not only as a mechanism for clothing production but also as a living archive of artistic expression, regional identity, and socio-economic resilience. The sector is especially vital to rural India, where weaving traditions have been passed down for centuries, embedding intricate technical knowledge within family and community lineages. According to the Fourth All India Handloom Census (2019–2020), 31.45 lakh households are engaged in handloom weaving, making it one of the largest unorganized industries in the country (Ministry of Textiles, 2020). The size of the sector highlights its cultural and economic value and shows how important it is for supporting rural communities.

Despite its historical prestige, the handloom sector faces serious structural and market challenges. Decentralization, which once allowed weaving to flourish across India, is now a concern because today's economy needs strong policy support, better access to funding, and infrastructure. Weak policies, limited financing, and poor market facilities have made it hard for the industry to compete with large-scale machine production (Lhoungu, 2021). Moreover, consumer awareness of authentic handmade goods remains quite low, with many unable to differentiate between the genuine craft and machine-made production (Kumudha and Rizwana, 2013; Prathap and Sreelaksmi, 2022; Paul and Goowalla, 2021). As a result, the sector struggles to balance preserving tradition with keeping up in a fast-changing market, and artisans often feel the most pressure from these changes.

The COVID-19 pandemic deepened the vulnerabilities within the handloom sector. Lockdowns, supply chain disruptions, and abrupt market closures interrupted the production cycles, resulting in prolonged income loss for the artisans. Handloom cooperatives and self-help groups, which already operated on narrow margins, faced devastating challenges. Many artisans were forced to abandon weaving temporarily for lower-paying wage labor (International Labour Organization, 2021). For communities deeply tied to the craft, this disruption was more than simply economic. Its cultural and emotional effect disrupted the transmittance of practices across generations. The Covid-19 crisis pushed the already struggling handloom economy over the edge, raising critical questions regarding its long-term sustainability.

The unchecked spread of counterfeit and machine-made products masquerading as handmade has become a significant issue for the sector. Powerloom textiles are often falsely branded as authentic handlooms. Their lower cost and faster production cycles disrupt and erode both the market value and cultural credibility of genuine handloom goods. For instance, handcrafted Pashmina shawls, which can command prices upward of ₹50,000 due to the labor-intensive process and heritage significance, face direct competition from machine-made imitations sold online for as little as ₹2,400 (Vhavle and Krishnappa, 2020). Such disruptions cascade to market failures, leading to the devious circle of artisans' inability to compete fairly, which leads to losing consumer trust, which forces crafts to lose their symbolic value and thus their history. Scholars have emphasized how counterfeits destroy craft and force cycles of economic marginalization in perpetuity.

The answer, according to experts and practitioners alike, is to tap into the potential of digital technologies to improve transparency, traceability, and renewed consumer engagement. Innovations like the Internet of Things (IoT), blockchain, artificial intelligence (AI), and cloud computing have been proposed as solutions to improve the supply chain integrity and enable producers to verify authenticity (Khubchandani, 2023). Beyond functional benefits, such technologies also have the ability to transform the consumer-producer interactions by fostering ethical consumption and allowing tales/stories spun from the roots. Sadly, much of the current literature tends to focus on the brand or institutional interventions, with barely any consideration on how artisans themselves experience, accept, and adapt. The voice of the artist, which is vital to the continuity of such heritage crafts, is often absent from mainstream discussions about digital innovation in textiles.

Digital adoption on the grassroots level has pushed the Indian handloom sector's potential to transform on the global trends platform. IoT-enabled devices have already proved themselves in agriculture by improving the supply chain traceability, optimizing production efficiency, and enabling real-time monitoring for small farmers. Similarly, the implementation of blockchain has been successful in the fair trade of commodities such as coffee and cocoa to establish origins, prevent counterfeiting, and transparent pricing processes. These examples demonstrate how digital infrastructures reinvent global value chains, especially by safeguarding producers while promoting their origins and identities. In this global trend, the Indian craft sector faces a critical decision: can we integrate these technologies without compromising the cultural integrity of traditional practices?

It is against this backdrop that KOSHA, a social-technology enterprise, has emerged with a targeted focus on the artisan economy. KOSHA AI is the entity behind the development of a comprehensive technology model that combines IoT, AI, blockchain, and cloud computing to address the authenticity and transparency challenges of the sector. The KOSHA suite includes innovations such as the HASTA IoT loom sensor, which authenticates weaving activity; wearable devices that record artisan-specific data for non-loom crafts such as embroidery and printing; and ScanLIVE, an augmented reality storytelling feature that connects consumers directly with artisan identities and production processes (Khubchandani, 2023). Unlike regular digital solutions, KOSHA's model is specifically made for traditional crafts, focusing on respecting artisans and ensuring fair economic practices while also being technically accurate.

Through the My E-Haat initiative, KOSHA's partnership with the HCL Foundation has facilitated the deployment of these tools in real-world artisan clusters. The technology's early adoption in Amravati and Barabanki, with expansion planned for Pochampally and other clusters, illustrates how it can be scaled within diverse craft traditions. Reports highlight that over 1,500 artisans are expected to benefit from the initiative, with outcomes including increased income stability, enhanced recognition, and improved bargaining power in markets. By embedding traceability into production cycles and linking products with tamper-proof digital identities, the system addresses counterfeit competition while creating new consumer experiences rooted in transparency and storytelling (HCL Foundation, 2022).

The integration of KOSHA's systems also reflects broader shifts in consumer preferences. Studies indicate that ethical and sustainable sourcing increasingly shape purchasing decisions in both domestic and global markets. By aligning authenticity verification with consumer demand for transparency, KOSHA's interventions position Indian handloom products within a premium segment that values provenance and craftsmanship. Importantly, this model demonstrates how heritage preservation and market competitiveness need not be mutually exclusive but can be strategically combined (India Retail, 2020).

Despite these promising developments, critical questions remain about how artisans themselves perceive and navigate these technological shifts. Existing scholarship often overlooks the lived realities of craftspeople who must integrate these tools into traditional workflows, negotiate new forms of visibility, and adapt to digital systems that may feel foreign to their cultural practices. When evaluating how emerging technologies shape communities, it's important to look beyond just financial metrics. One needs to consider what happens to people's sense of identity and personal worth and how knowledge passes between generations, especially in places where traditional craftsmanship remains central to life.

This study fills an important gap by examining real experiences of artisans working with KOSHA and the HCL Foundation. Rather than focusing on abstract concepts, the research draws directly from craftspeople's own stories about their work. It explores concrete questions: how do digital tools change the way their work is authenticated, who they can sell to, how they see themselves, and whether they can keep adapting to stay relevant? The methodology combines fieldwork observations, direct conversations with artisans, their personal accounts, and data from the organizations involved, creating a fuller picture of what digital tools actually mean for people doing craft work day to day.

This approach engages with three important debates in academic circles. On one level, it shifts the conversation about technology and creative industries away from what organizations are doing and toward what individual craftspeople themselves are choosing and learning. It also connects what's happening with Indian textiles to broader global patterns we're seeing in farming and ethical trade networks, helping us understand crafts within an international context rather than in isolation. Finally, it demonstrates that companies like KOSHA, when they work as part of larger development efforts, can show us a path forward, one where traditional practices and modern tools don't have to be at odds.

Perhaps most importantly, this work challenges how we think about traditional crafts. Instead of viewing them as endangered practices that need protecting, it presents evidence that they're actually dynamic and creative, perfectly capable of competing and succeeding online. By centering what artisans themselves have to say, the research suggests that when communities are genuinely involved in deciding how technology gets used, and when those choices are made thoughtfully, the result can be both stronger cultural traditions and better economic stability for people in one of humanity's oldest craft heritage sectors.

Methodology

This study adopts a qualitative case study design to examine the integration of digital technologies into India's traditional craft sector. Grounded in the lived experiences of artisans, it explores how authenticity, recognition, and sustainability are negotiated through digital adoption at the grassroots. KOSHA, a social-tech enterprise, has developed the technological tools, and the HCL Foundation, through its My E-Haat initiative, has facilitated their deployment across artisan clusters. At the time of research, more than 1,500 artisans across five clusters were engaged under two distinct models: the HASTA IoT device for handloom weaving and the HASTA wearable device for embroidery, hand printing, and other surface crafts (Kosha, 2023).

The case study approach was selected for its ability to provide in-depth, contextualized analysis of complex socio-technical dynamics in natural settings. India's handloom and craft sector represents such a context, where cultural traditions, market pressures, and digital innovation intersect. Informed by interpretivist traditions, the research design emphasizes artisan perspectives as central to understanding technological change.

The study draws on both secondary and primary data. The secondary data included organizational reports, program presentations, and implementation materials, providing contextual grounding and details of scale, models, and rollout. The primary data collection entailed on-site observations, semi-structured interviews with artisans, and testimonial documentation. On-site observations were conducted in HCL Foundation's intervention clusters engaged in *khadi*, cotton weaving, and linen crafts in Amravati and Barabanki. These field visits examined how technology was embedded into daily production environments. Particular attention was given to workspace arrangements, tool placement, and the rhythm of weaving or crafting alongside digital interfaces. Observational notes also documented group dynamics and instances of peer-to-peer learning, particularly where younger artisans assisted elders in adapting to wearable or digital systems. A total of 50 beneficiaries were interviewed across the clusters. Interviews followed an open-ended guide designed to elicit artisan perspectives on authenticity, pricing, market access, recognition, and ease of technological use. While artisans described practical changes, they also shared reflections on emotional and cultural dimensions, such as how visibility through digital storytelling altered their sense of dignity and professional identity. Artisans' experiential accounts were complemented by testimonial narratives collected during the implementation phase. Real-time documentation of authenticated product lifecycles, such as digital videos generated by wearable devices and tamper-proof labels, was analyzed to understand how authenticity was communicated to consumers.

The mixed-methods approach enabled the triangulation of data, enhancing both validity and depth by integrating experiential, observational, and documentary evidence. Ethical protocols were integral to the study's design. All participants were informed about the voluntary nature of their involvement, and informed consent was obtained prior to data collection. This framework was chosen to systematically interpret how technological adoption was experienced not only economically but also socially and culturally.

This methodological approach addresses a critical gap in existing knowledge. Much of the literature on digital innovation in textiles emphasizes technical efficacy or institutional adoption while neglecting the lived experiences of artisans who must adapt these systems to traditional workflows. By integrating field-level narratives with organizational documentation, this study captures the layered realities of technological adoption: the technical promise of IoT and blockchain, the institutional scaffolding provided by HCL Foundation, and the grassroots perspectives of artisans negotiating dignity, recognition, and sustainability.

Results and Discussion

This study explores digital integration in the craft sector from the perspectives of artisans, grounded in their lived experiences. The Indian craft economy, traditionally marginalized within global fashion narratives, is now experiencing what can be described as a technological renaissance. Through the integration of KOSHA's platforms, HASTA IoT devices for weaving, HASTA wearable systems for embroidery and surface embellishment, and ScanLIVE augmented storytelling, artisans are witnessing significant changes in how their work is validated, represented, and positioned in markets. These interventions do not simply digitize production processes; they redefine artisans' roles in supply chains, offering avenues for authenticity, recognition, and more stable economic participation.

Findings are presented across four thematic lenses: authenticity validation, market access and pricing power, artisan identity and recognition, and technological adaptability and ease of use, alongside attending to challenges such as digital literacy, cost, and generational divides. This discussion integrates practitioner insights, secondary documentation, and artisan testimonials to provide a holistic analysis of this transition.

Authenticity validation: securing cultural and market legitimacy

The handloom and craft sectors have long suffered from market distortions caused by mechanized and counterfeit products masquerading as handmade. Imitation pashmina and other handcrafted products are often sold at a fraction of the cost of genuine handlooms, misleading consumers and eroding trust in handmade markets. In this context, KOSHA's authentication systems address a structural vulnerability by providing verifiable proof of handmade origin. The HASTA IoT loom sensor records the rhythm of manual weaving, distinguishing it from powerloom outputs. Similarly, the HASTA wearable device authenticates artisan labor in embroidery, hand printing, and other surface crafts. These systems link real-time data to blockchain infrastructure, producing tamper-proof records of authenticity accessible via digital labels.

Many artisans emphasized the significance of this shift. For many, authentication represented not just technical proof but moral validation of their work. One weaver from Amravati expressed, "What we make by hand is better than machine-made. Now, thanks to this device, people actually know who made their clothes and how they were made. Getting recognized like this helps us earn more and feel proud. It's not just about selling stuff. It's about being noticed."

The recognition really matters. In the past, most artisans simply didn't have a way to prove that their crafts were different from cheap knock-offs. With authentication, they can finally stand up for their work. Authentication operates as a counter-narrative to market invisibility. However, artisans expressed caution. Several noticed that, while authentication strengthened legitimacy in niche markets, it did not immediately eliminate widespread customer apathy toward handmade products. Some artisans pointed out that while these tools help in specialty markets, most regular shoppers still care way more about price than anything else. Unless a customer is looking for proof of authenticity, fakes and cheap goods will keep finding buyers. As one cooperative leader pointed out, provenance tools are only useful if clients consider authenticity a purchase aspect. Counterfeiters may continue to exert pressure in mainstream regions where price sensitivity reigns supreme. Another challenge lies in the financial sustainability of these systems. Although initial deployments were subsidized under HCL Foundation's partnership, artisans raised concerns about the long-term costs of devices, maintenance, and connectivity. For many working on thin margins, the risk of technology becoming another layer of dependency was noted with caution. Despite these challenges, authentication represents a fundamental breakthrough in aligning artisan credibility with verifiable evidence. It offers a way to stand out and build trust in a world full of look-alikes. As shared by Tarai and Shailaja (2020), this is a chance to finally get noticed for real skill and effort, not just fade into the background in a crowded retail landscape.

Market access and pricing power: from survival to premium positioning

The second thematic lens examines how authentication translates into market access and improved bargaining power. By embedding provenance data into tamper-proof labels and QR codes, KOSHA enables artisans to connect their products to narratives of origin, quality, and sustainability. This shift repositions artisans from undifferentiated producers to participants in premium and ethical markets. Program data show measurable impacts. In the Amravati cluster, authenticated production capacity expanded to 2,500–3,000 meters annually, creating a more reliable supply base for retailers. Artisans reported increased order volumes, particularly from ethical brands and social commerce platforms seeking verified products. This is consistent with studies indicating consumer trust in transparent and ethically sourced products can lead to premium pricing and recurring purchases (Bonderud, 2025).

For artisans, the impacts were immediate. One recorded statement reflects this transformation: "Previously, we had to accept whatever price was offered, because people queried whether our work was truly handmade." Now that we have that evidence, we can negotiate more effectively. Customers are also more assured, and we no longer have to constantly compete with machine-made products." Such outcomes imply a power shift in favor of producers, reducing reliance on middlemen, who frequently capture excessive value. By basing pricing on proven authenticity, craftspeople can claim margins that reflect both labor intensity and cultural worth. Yet challenges persist. Interviews revealed concerns about over-dependence on niche ethical markets, which, while lucrative, remain limited in scale compared to mass consumer demand. Additionally, some artisans questioned whether digital tools would guarantee consistent price premiums, especially in rural markets where consumers remain less attuned to concepts of traceability.

Generational divides also surfaced. Younger artisans expressed enthusiasm about linking their work to global buyers through digital labels, while older weavers feared being excluded from market opportunities if unable to adapt to QR-based systems. This suggests that while pricing power has improved, market inclusion is contingent upon addressing digital literacy gaps. Additionally, leveraging this authenticity, KOSHA has enabled artisans to access global markets, including collaborations with the Design Museum London and the World Economic Forum (HCL Foundation, 2022). Analysis suggests that authentication-driven transparent transactions yield economic and symbolic capital. It improves financial stability, connects artisans to ethical supply chains, and is consistent with global trends in sustainable consumption.

Artisan identity and recognition: from invisible labour to visible creators

Perhaps the most profound impact of KOSHA's systems lies in how they reshape artisans' social identity and recognition. Historically, artisans have been marginalized as invisible laborers within extended supply chains. Finished goods reached markets stripped of their makers' names, stories, or cultural context. The introduction of ScanLIVE augmented reality storytelling directly challenges this invisibility. By scanning tamper-proof tags, consumers access digital profiles, videos of production processes, and artisan narratives. This transforms consumption into a relational experience, reconnecting buyers with the humanity of producers.

The emotional resonance of this feature was repeatedly emphasized in artisan testimonials. A weaver from Barabanki expressed, "Earlier, our work was never recognized. Now, when people scan the tag, they see our faces, our names, and our process. Such recognition gives us dignity. Customers respect us more, and we feel proud that our identity is part of the product." The case of Sonali Prakash, a 24-year-old artisan from Amravati, illustrates the point vividly. By sharing her story through the Kosha app, Sonali connected directly with urban buyers, reigniting interest in her craft and repositioning herself not as an anonymous laborer but as a creative entrepreneur.

Recognition is not merely symbolic. Several artisans associated visibility with improved self-esteem, bargaining power, and intergenerational pride. For example, one artisan reflected that her children, once dismissive of weaving as an unviable livelihood, now viewed it as a respected profession after seeing her name attached to authenticated products. This aligns with Nussbaum's (2011) argument that true development requires expanding individuals' capabilities, including the ability to live with dignity and self-respect, rather than focusing solely on economic outcomes. Nonetheless, challenges persist. Some artisans expressed fear that their constant visibility could expose them to competition or exploitation, particularly if their profiles circulated without their consent. Others expressed concern about the sustainability of storytelling, whether consumer interest would wane over time, reducing identity recognition to a transient marketing tool. Despite these limitations, the introduction of artisan-centered narratives represents a paradigm shift. It reconfigures value chains to foreground the human element of craft, transforming invisible labor into visible creativity.

Technological adaptability and ease of use: negotiating change

The final thematic lens addresses how artisans adapted to new technologies and the challenges encountered. While the benefits of authentication and recognition were widely acknowledged, adoption faced some hesitation. Initial apprehension was common, particularly among older weavers unaccustomed to digital devices. Some feared that technology might disrupt traditional rhythms or require skills beyond their capacity. An artisan shared that "The elders were skeptical at first. They thought the device would slow them down or replace their skills. But when they saw it work quietly in the background, they accepted it."

Training and support mechanisms facilitated by the HCL Foundation were critical in bridging these divides. Younger artisans often acted as intermediaries, helping elders navigate devices and interpret digital labels. Over time, the program fostered intergenerational collaboration rather than exclusion. Testimonials highlight this transition. One artisan from Amravati, Durga, recounted, "At first, I did not understand the device. But with training, I gained confidence. Now my earnings have improved, and I feel proud that my work is valued." Her income reportedly rose to INR 6,000 per month, underscoring the tangible impact of adaptation on livelihood security. Still, challenges remain. Some artisans raised concerns about the costs of devices, reliance on external maintenance, and uneven digital literacy. Connectivity gaps in rural areas also impeded smooth use of cloud-linked systems. Moreover, artisans expressed concerns about over-reliance on technology providers and the potential consequences of withdrawing external support.

These apprehensions reflect the "double-edged nature of technological change" in craft economies: while innovations enhance resilience, they also introduce new dependencies and vulnerabilities. Overall, artisans expressed cautious optimism. They valued tools that complemented rather than replaced traditional practices, favoring systems that amplified human creativity rather than automated it. This preference reflects a broader principle of coexistence: technology is accepted when it respects craft rhythms and cultural autonomy. This aligns with Luckman's (2015) observation that digital tools in craft sectors can both empower artisans and risk undermining the embodied, place-based knowledge that defines their creative identity.

Synthesis: beyond functional benefits

The findings suggest that digital technologies in craft economies cannot be reduced to functional benefits such as improved pricing or operational efficiency. For artisans, these systems are deeply tied to identity, dignity, and cultural continuity. Authentication validates the handmade nature of their work, market transparency enhances economic resilience, storytelling restores visibility, and adaptability demonstrates resilience amidst change. Yet these benefits coexist with persistent challenges such as digital literacy gaps, generational divides, cost burdens, and risks of dependency. By centering artisan perspectives, this study underscores the dual nature of digital integration: it is both an enabler of empowerment and a site of negotiation. Artisans interpret technology not as a replacement but as an affirmation of their relevance in a rapidly digitizing economy. In doing so, the study advances understanding of how heritage and innovation can coexist. It illustrates that technology, when co-created and implemented with sensitivity, can reinforce cultural economies without eroding their human essence.

Conclusion

The integration of KOSHA's technological systems into India's traditional craft sector illustrates how digital innovation, when thoughtfully designed and collaboratively implemented, can address structural vulnerabilities while safeguarding cultural heritage. Rather than displacing artisanal knowledge, these tools enhance the credibility, visibility, and economic viability of handmade production, demonstrating that modernization need not equate to mechanization or cultural erosion.

By embedding end-to-end traceability through IoT devices, blockchain-led provenance systems, and augmented reality storytelling, KOSHA provides artisans with the means to validate authenticity, strengthen market positioning, and reclaim their identities as creators rather than anonymous laborers. The testimonies of artisans, who describe feeling "recognized for the first time" or newly able to "defend fair prices with confidence," underscore that the benefits of such innovations extend beyond technical validation. They are deeply tied to dignity, cultural continuity, and intergenerational pride. These findings resonate with global parallels in grassroots innovation. Just as IoT-enabled supply chains in agriculture have enhanced efficiency for smallholder farmers and blockchain systems have reinforced transparency in fair-trade commodities such as coffee and cocoa, KOSHA's interventions situate artisans within broader ethical consumption movements. Yet, what distinguishes this case is its artisan-first orientation, where technology is created to amplify craft traditions rather than override them.

The partnership with the HCL Foundation has been instrumental in scaling these innovations responsibly. By facilitating deployment across five clusters and supporting over 1,500 artisans, the Foundation ensures that technical tools are embedded within supportive ecosystems of training, market linkage, and fair pricing advocacy. This cross-sector collaboration illustrates how private innovation and social sector facilitation can converge to generate outcomes that are both economically sustainable and socially equitable. Artisans highlighted barriers related to digital literacy, affordability of devices, and generational divides in adapting to new systems. Connectivity gaps and concerns about dependency on external providers also signal that technological adoption is neither seamless nor risk-free. However, the cautious optimism expressed by participants suggests that these challenges can be mitigated when innovation respects existing craft rhythms, builds local capacity, and preserves creative autonomy.

This study affirms that sustaining craft economies requires balancing global competitiveness with cultural authenticity. By safeguarding artisans from counterfeit-driven erosion and embedding them within ethical value chains, KOSHA demonstrates how heritage and technology can operate in synergy. As demand for authenticity and traceability rises, such initiatives signal a paradigm shift where innovation is inclusive, equitable, and creativity-driven, ensuring traditional legacies thrive as vital assets of a sustainable future.

Acknowledgment

The authors used QuillBot solely for paraphrasing purposes in limited sections of the manuscript. The use of the tool was restricted to linguistic refinement, and the intellectual content, analysis, and interpretations remain entirely the authors' original work. The authors take full responsibility for the content of this article.

References

Bonderud, D., 2025. *Brand trust makes 87% of shoppers pay more for products — here's why.* Salsify [Blog] Available at: <https://www.salsify.com/blog/why-brand-trust-makes-shoppers-pay-more> [Accessed 10 October 2025].

HCL Foundation, 2022. *Leveraging technology for the authentication of crafts.* Unpublished internal report. HCL Foundation.

India Retail, 2020.*Transparency is key for clothing and home textiles brands to win consumer trust and confidence: Survey.* India Retailing. [online] Available at: <https://www.indiaretailing.com/2020/09/03/transparency-is-key-for-clothing-and-home-textiles-brands-to-win-consumer-trust-and-confidence-survey/> [Accessed 10 September 2025].

International Labour Organization, 2021. *Situation analysis on the COVID-19 pandemic's impact on enterprises and workers in the formal and informal economy in India*. ILO DWT for South Asia & Country Office for India, New Delhi. [online] Available at: <https://www.ilo.org/wcmsp5/groups/public/---asia/---ro-bangkok/---sro-new-delhi/documents/publication/wcms_798079.pdf> [Accessed 24 October 2025].

Khubchandani, S., 2023. Talking traceability with Kosha. *Creative Dignity*. [online] Available at: <https://www.creativedignity.org/talking-traceability-with-kosha/> [Accessed 12 September 2025].

Kosha, 2023. *Technology-based interventions: Kosha.* Unpublished internal document. Kosha.

Kumudha, A. and Rizwana, M., 2013. A study on consumer awareness about handloom products with special reference to Erode District. *Journal of Marketing and Consumer Research*. [online] Available at: <https://iiste.org/Journals/index.php/JMCR/article/view/9221> [Accessed 10 September 2025].

Lhoungu, V., 2021. Economic perspective of traditional handloom and handicraft: A case study of NHHDC, *ShodhKosh: Journal of Visual and Performing Arts*, [e-journal] 2(2), pp. 201-210. https://doi.org/10.29121/shodhkosh.v2.i2.2021.2295.

Luckman, S., 2015. *Craft and the creative economy.* London: Palgrave Macmillan.

Ministry of Textiles, 2020. *Fourth national handloom census of weavers and allied workers 2019–2020.*Office of the Development Commissioner (Handlooms), Ministry of Textiles, Government of India. [online] Available at: <https://handlooms.nic.in/assets/img/Statistics/3736.pdf> [Accessed 12 October 2025].

Nussbaum, M.C., 2011. *Creating Capabilities: The Human Development Approach.*Cambridge: Harvard University Press

Paul, R. and Goowalla, H., 2021. *A study on consumer awareness of handloom products with special reference to Dimapur District, Nagaland*. *International Journal of Management Studies (IJMS),* [online] 5(2(3)), pp.45–54. Available at: <https://www.researchersworld.com/index.php/ijms/article/view/1766> [Accessed 10 October 2025].

Prathap, S.K. and Sreelaksmi, C.C., 2022. Determinants of purchase intention of traditional handloom apparels with geographical indication among Indian consumers. *Journal of Humanities and Applied Social Sciences,* [e-journal] 4(1), pp.21–38. https://doi.org/10.1108/JHASS-04-2020-0055.

Tarai, S.K. and Shailaja, K., 2020. Integration of E-Commerce in Handloom Sector: Consumer Perspective in Odisha, India. *Journal of Textile and Apparel Technology and Management*, 11(4). [online] Available at: <https://jtatm.textiles.ncsu.edu/index.php/JTATM/article/view/17975> [Accessed 24 October 2025].

Vhavle, A. and Krishnappa, V., 2020. *Akerlof's lemons and the handloom market*, Kosha.ai, [online] Available at: <https://www.kosha.ai/post/akerlof-s-lemons-and-the-handloom-market> [Accessed 12 October 2025].

About the authors

Satabdi Roy is a dedicated development specialist with over seven years of experience in the development sector. Her career reflects a deep commitment to advancing social development through meaningful contributions to research institutes such as NIRD and PR, Hyderabad, and the Institute of Life Sciences, Bhubaneswar, as well as social purpose organizations like WASSAN and the VisionSpring Foundation. Currently, she is associated with the HCL Foundation, and her expertise lies in fostering sustainable partnerships and effective program management. She has been key in managing various national and state-level project reporting. She holds a professional certificate in Development Management from the Indian School of Development Management (ISDM), Noida, and a master's degree in Development Studies from NIT Rourkela.

satabdi.roy@hcltech.com

Gaurav Majumdar holds 12+ years of experience in the development sector with national and international development organizations in different verticals. He previously worked with the State Rural Livelihood Mission, Bihar, 'Jeevika,' and the Office of Refugee and Resettlement in Chicago. He serves as the technical lead for the skill development and livelihood thematic area, as well as the special initiative called My E-Haat, at HCL Foundation. Gaurav holds a master's in business administration (rural management) from KIIT University, Bhubaneswar, and a master's in public administration from Illinois Institute of Technology, Chicago, US. He has published three articles on the My E-Haat initiative, which were also presented at NIFT, Kangra, and IICD, Jaipur.

gaurav.majumdar@hcltech.com

Vikas Dargan has been working in the crafts and cultural sector for over seven years. His previous experience includes working with the Indian National Trust for Cultural Heritage (INTACH) and the Cultural Conservation Consultants Firm, where he gained extensive experience in projects related to craft revival, cultural management, architectural heritage restoration, and craft research. Currently, he is leading My E-Haat, a special initiative of the HCL Foundation. Vikas is a trained architect holding a postgraduate diploma in Built Environment from Anant National University, Ahmedabad; a postgraduate diploma in Cultural Management from IGNCA Delhi; and an executive master's in Business Analytics from IIM Indore.

vikas.dargan@hcltech.com

Development of Framework for Feasibility Study of Fabrication of Spare Parts Using Fused Deposition Modeling: A Delphi Approach

Abhilasha Singh, Prabir Jana and Deepak Panghal

Abstract

Additive Manufacturing (AM) has paved its way into various fields like manufacturing, healthcare, aerospace, etc., due to the advantages it provides over traditional manufacturing. It has been an interest area for many researchers for years, and several studies have been conducted to analyze the feasibility of manufacturing products using additive manufacturing. However, there is a gap in the study for manufacturability analysis, particularly for Fused Deposition Modeling (FDM), a method under Additive Manufacturing (AM). FDM, or material extrusion, offers the least expensive and simple installation, setup, and training.

This article tries to fill the gap by identifying the attributes and parameters specifically concerned with FDM. The outcome of this research is a manufacturability assessment framework for FDM, which can be used to evaluate whether the object is suitable to be manufactured by the FDM process or traditional manufacturing. First, all the attributes are collected by secondary research. Thereafter, a Delphi study was conducted to find out the factors that are relevant to FDM. The panel comprised experts from various fields like industry, academia, and the research domain. The attributes identified in the Delphi study were subjected to exploratory factor analysis to find the interconnection among the attributes and identification of factors. Finally, a framework with various screening levels was developed with the help of factors and attributes identified in the previous step. The final structured framework has five levels of screening based on process, machine, and material feasibility (level 1), functional feasibility (level 2), design potential (level 3), business potential (level 4), and environment (level 5). A component needs to qualify for all the levels to receive a go-ahead decision for FDM.

The framework would be useful as a practical tool to assess the manufacturability of a part to be printed by FDM in the early-stage product development cycle. The garment

industry cannot afford to make a wrong decision and restart the process due to high variability and a very short fashion cycle. This framework would eliminate the risk of product failure, thereby saving money, time, and effort.

Keywords: Fused deposition modeling, Delphi method, exploratory factor analysis, manufacturability analysis, 3D printing, spare parts

Introduction

Additive Manufacturing (AM) has found its application in almost every field. To adopt and adapt to Industry 4.0, manufacturers seem very inclined towards switching to advanced manufacturing techniques like AM from the conventional techniques. AM offers several benefits over conventional techniques. The authors of the bestseller Fabricated—Lipton and Kurman (2018)—summarize AM into ten principles: 1) Manufacturing complexity is free, 2) Variety is free, 3) No assembly required, 4) Zero lead time, 5) Unlimited design space, 6) Zero skill manufacturing 7) Compact, portable manufacturing, 8) Less waste by-product, 9) Infinite shades of materials, and 10) Precise physical replication. These principles are the foundation of identifying AM potentials.

Prof. Ian Gibson, David Rosen, and Brent Stucker, noted authors in the field of AM, list several benefits of this technology, which is based on the WYSIWYB (What You See Is What You Build) approach and is similar to the WYSIWYG (What You See Is What You Get) approach used in 3D CAD. Also known by other popular names, such as direct digital manufacturing, rapid prototyping, and 3D printing, AM simplifies the multi-stage and multi-resource processes of the traditional method. (Gibson, Rosen and Stucker, 2015).

As with any other manufacturing technique, AM has certain limitations too. In some cases, the limitations can be overcome by changing the material or the design. In other cases, it seems more prudent to opt for conventional manufacturing techniques rather than AM. The latter scenario calls for a screening process or feasibility check for the part being considered for AM. Many researchers have proposed a process to identify the general potential for fabrication using AM. A detailed study is included in the literature review.

This research proposes a comprehensive screening process for spare parts for Fused Deposition Modeling (FDM). Proposed processes by ISO/ASTM (International Organization for Standardization/American Society for Testing and Materials) and other researchers have been studied. Thereafter, all the criteria have been listed down. Classification has been done according to the impact areas. The weights have been assigned with the help of experts using the Delphi method, and finally, a framework for the FDM potential scorecard has been proposed. The proposed scorecard will assist the manufacturers in making swift decisions regarding the FDM manufacturing of the selected part.

Literature Review

Vaneker, et al. (2020) have divided the DfAM framework into three stages: AM suitability exploration, product (re)design for AM goals, and geometry optimization to enable the product realization chain. The AM suitability exploration stage helps the designer to evaluate and identify go/no-go decisions for AM, as it needs to be understood that not all the parts selected can be eligible candidates for AM. There might be some requirements of design, process parameters, and other changes before the part can be additively manufactured. In some cases, it may be cost-effective; in others, it may not. AM suitability exploration also facilitates the identification and resolution of manufacturability issues, as shown in Figure 1.

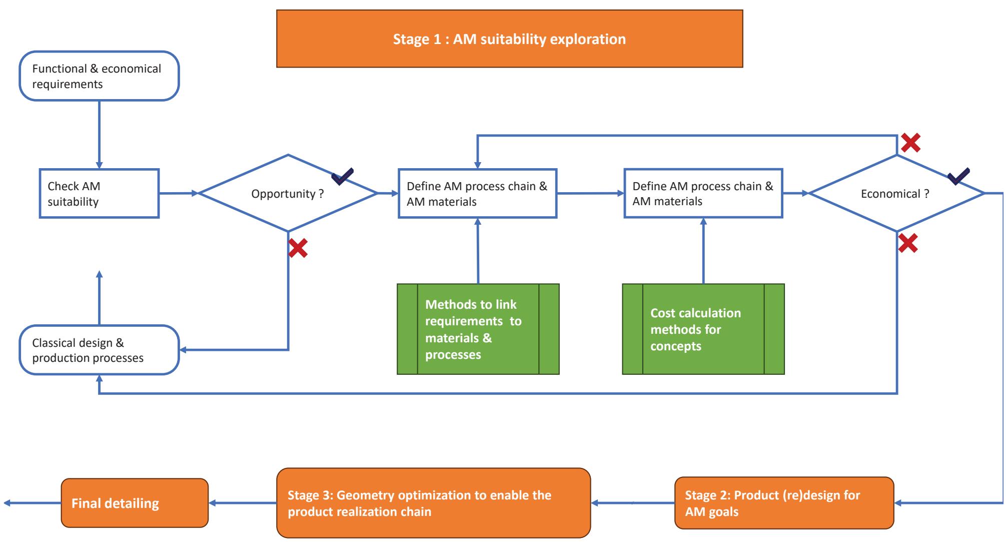


Figure 1: AM suitability exploration

Source: Vaneker et al., 2020

Hague, Mansour and Saleh (2003) have tried to highlight the advantages that AM has to offer. In the course of the project, they have emphasized design complexity, design freedom, material properties, and the changes to the design. Contrary to the previous definition of design complexity that included manufacturing cost, assembly cost, serviceability, etc., researchers have established that design complexity particularly refers to the shape complexity, and shape is the combination of geometry and topology, as the previous definition does not stand correct in terms of rapid prototyping. Design freedom means that the design limitations are removed when it comes to AM as compared to conventional manufacturing. Finally, as part of the analysis of the material properties, flexural, tensile, and impact tests need to be performed.

Taking the benefits that AM has to offer as a base, Schneck et al. (2019) have identified the enablers and the objectives that they fulfil. Initially they identified 64 impact factors and then clustered the factors into four implementation levels, viz., product, process chain, life cycle, and company. Apart from clustering into different levels, the researchers also categorized the collected benefits into enablers and objectives. Enablers described the technical aspects of AM, while objectives referred to the benefits that would be gained by the application of AM to the business case. After merging the similar benefits, 11 enablers and 10 objectives were identified as in Table 1 and Figure 2.

Table 1: Enablers and objectives in four implementation levels

Enabler ➔	**Objective (Improvement in…)**
Product – 1st level	
E11- Individualization	011- Part performance
E12- Improvement of design/ aesthetics	012- Lifetime
E13 – Functional integration	013- Maintenance
E14 – Improvement of thermodynamic behavior	
E15 – Reduction of component mass	
E16 – Improvement of mechanical/ flow behavior	
Process Chain – 2nd level	
E21 – Simplified manufacturing process	O21- Manufacturing
E22 – Production on demand	O22- Lead time
Life Cycle – 3rd Level	
E31 – Faster product development	O31 – Development
E32 – Decentralised production	O32 – Logistics, installation & recycling
	O33 – Sustainability & emissions
Company – 4th Level	
E41 – Development of new business models	O41 - Image
	O42 – Business case

Source: Schneck et al., 2019

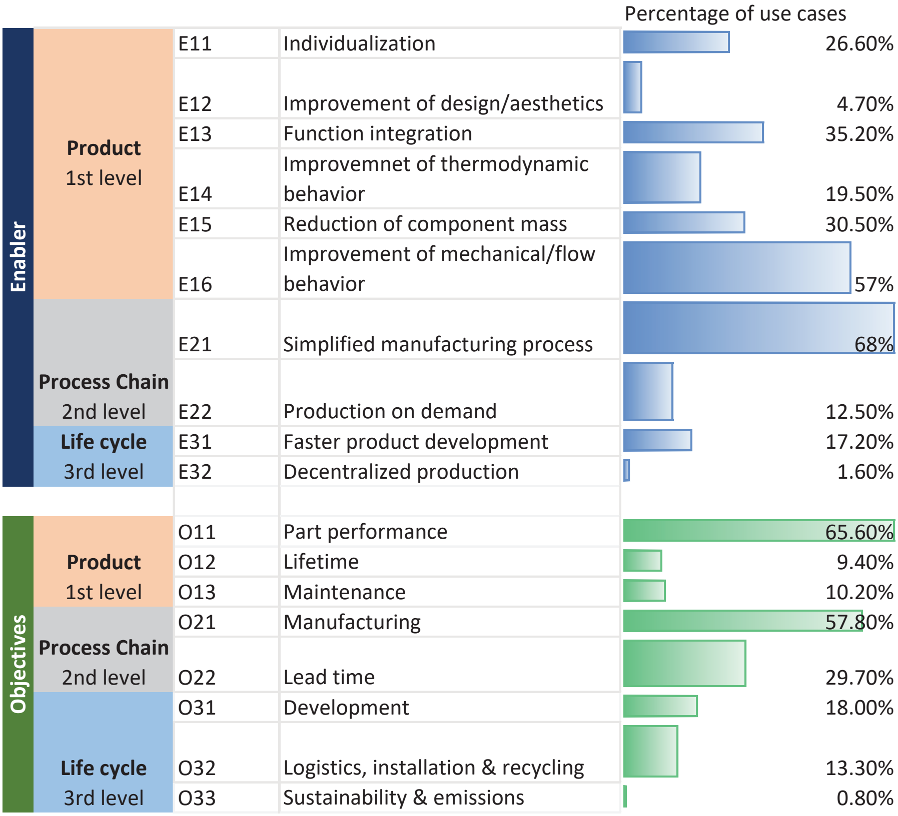


Figure 2: Use of enablers and objectives in industry application
Source: Schneck et al., 2019

Kumke, Watschke and Vietor (2016) have proposed a new classification of DfAM in their research based on the approaches—DfAM in the strict sense and DfAM in the broad sense. While DfAM in the strict sense includes the approaches concerning the product design, DfAM in the broad sense includes additional approaches apart from the core design. One of the components of DfAM in its strict sense is the utilization of AM potentials, which entails the elimination of manufacturing constraints to improve product performance, reduce manufacturing and material costs, and identify items or features that are difficult to manufacture using conventional methods. DfAM in the broad sense talks about the process selection, production strategy, manufacturability analysis, and selection of parts/applications based on strategic attributes like complexity, customization, and volume.

In the overall strategy for design for AM laid down by ISO/ASTM (2018), identification of general AM potential forms one of the crucial preliminary stages. Various aspects like material feasibility, build volume, improvement of functionality, and identification of potentials like customization, lightweight, internal structures, functional integration, designed surface structures, and specific material options are analyzed. As per ASTM, at least one item should display a high or medium potential to proceed with the decision to use AM. Lastly, other factors, like finances and business, are also considered for the final decision. Figure 3 shows a flowchart of the procedure for identifying AM potentials.

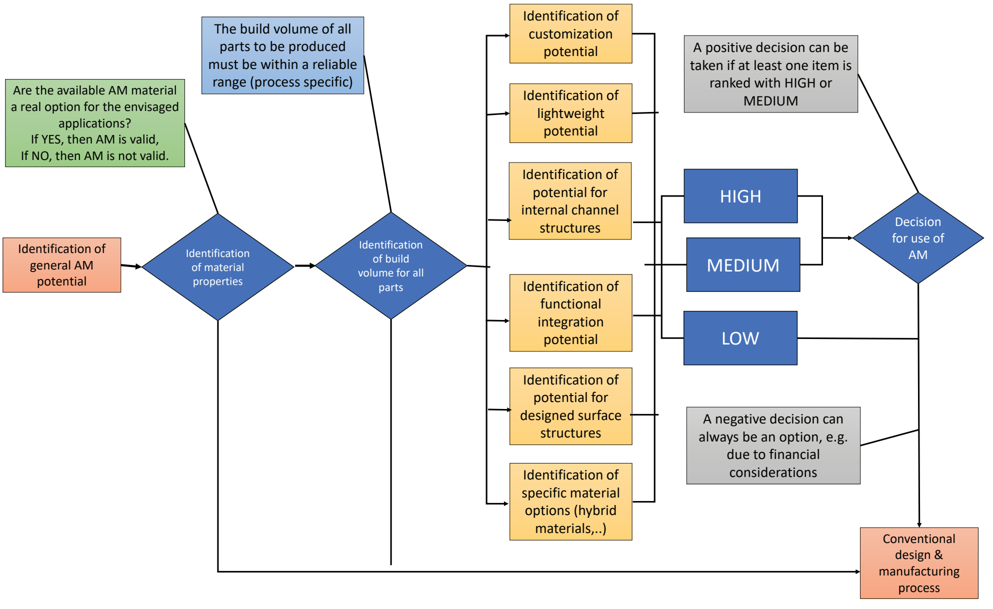


Figure 3: Procedure for identification of AM potential
Source: ISO/ASTM, 2018

Pradel et al. (2018) examine the AM potential and find out that the factors that are important are surface finish, dimensional accuracy, and consistency as compared to the conventional manufacturing process. Furthermore, some of the major concerns that are highlighted in the trade-off with light weightiness are the product durability and how the product would respond when exposed to various environmental conditions like daylight, humidity, temperature fluctuations, etc. When choosing the AM process among the seven processes defined by ASTM, important parameters to consider are machine availability, precision, surface finish, build size, feature size, printing speed, part strength, durability, post-processing, and cost of printing. Small batch size, along with complex geometry, is emphasized because AM provides an advantage over economies of scale; specifically, production costs remain the same regardless of batch size (Montero et al., 2020).

Thomas and Gilbert (2014) have conducted a detailed study on how AM can be cost-effective as compared to traditional manufacturing. They have categorized the benefits into three categories: ill-structured cost, well-structured cost, and product enhancement and quality. Ill-structured cost consists of inventory and transportation, the consumer's proximity to production, supply chain management, and vulnerability to supply disruption, while well-structured cost consists of material cost, machine cost, build envelope and envelope utilization, build time, energy consumption, and labour. In product enhancement and quality, limitations of AM, like support structure, heat dissipation, accuracy, surface finish, and feature details, are highlighted.

Development of the Framework for Objective Evaluation of FDM Potential

To fully leverage the advantages of a manufacturing process and avoid its pitfalls, one must objectively evaluate the potential for manufacturing the selected object using that process. This rule also applies to additive manufacturing before making a final decision. For objective evaluation, a framework was developed. The methodology adopted for developing the framework is presented in Figure 4.

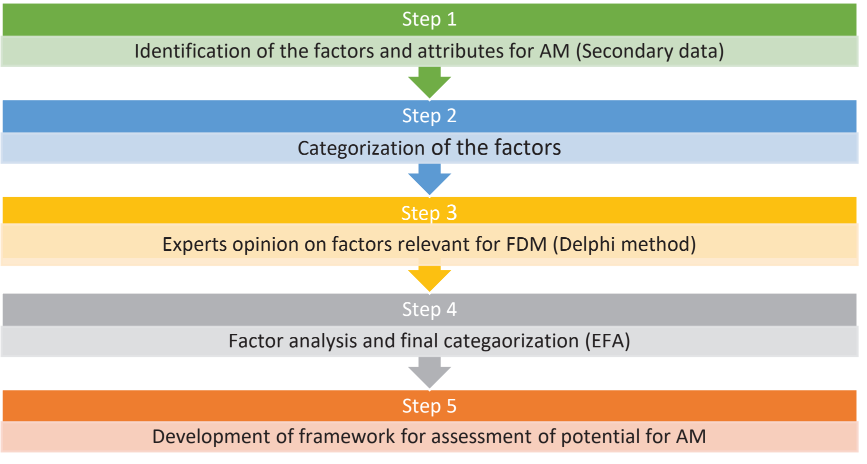


Figure 4: Methodology for framework development

Step 1: Identification of the factors and attributes for AM (Secondary data)

After a comprehensive review of the factors and parameters identified by various researchers for AM, a total of 80 factors were identified in phase one as listed in Table 2.

Table 2: Attributes identified through secondary data

S.No.	Factors	References
1.	Design complexity	(ISO/ASTM, 2018; Schneck et al.,2019; Vaneker et al., 2020)
2.	Design freedom	(ISO/ASTM, 2018; Vaneker, et al., 2020)
3.	Feature size	(Hague, Mansour and Saleh, 2003; Schneck, et al., 2019; Vaneker, et al., 2020)
4.	Object size	(Pradel, et al., 2018; Schneck, et al., 2019; Vaneker, et al., 2020)
5.	Build time	(FormLabs, 2021; Gibson, Rosen and Stucker, 2015; Hague, Mansour and Saleh, 2003)
6.	Build volume	(Gibson, Rosen and Stucker, 2015; Pradel, et al., 2018; Vaneker, et al., 2020)
7.	Machine availability	(Gibson, Rosen and Stucker, 2015; Kumke, Watschke and Vietor, 2016)
8.	Material availability	(ISO/ASTM, 2018; Kumke, Watschke and Vietor, 2016; Vaneker, et al., 2020)
9.	Multi-material	(ISO/ASTM, 2018)
10.	Heat dissipation	(ISO/ASTM, 2018)
11.	Flexural strength	(ISO/ASTM, 2018)
12.	Tensile strength	(ISO/ASTM, 2018)
13.	Impact strength	(ISO/ASTM, 2018)
14.	Lead time	(Kumke, Watschke and Vietor, 2016)
15.	Product life	(Kumke, Watschke and Vietor, 2016)
16.	Batch size	(Kumke, Watschke and Vietor, 2016)
17.	Supply chain management	(Hague, Mansour and Saleh, 2003)
18.	Vulnerability to supply chain	(Hague, Mansour and Saleh, 2003)
19.	Consolidation	(Hague, Mansour and Saleh, 2003)
20.	Accuracy	(Thomas and Gilbert, 2014)
21.	Precision	(Thomas and Gilbert, 2014)
22.	Conceptualization	(Hague, Mansour and Saleh, 2003)
23.	Shop floor complexity	(Rosen, 2014)
24.	Maintenance	(Thomas and Gilbert, 2014)

S.No.	Factors	References
25.	Design improvement/ aesthetics	(Thomas and Gilbert, 2014)
26.	Support structure	(Pradel, et al., 2018; Vaneker, et al., 2020)
27.	Post-processing	(Gibson, Rosen and Stucker, 2015; Hague, Mansour and Saleh, 2003)
28.	Assembly time	(Hague, Mansour and Saleh, 2003)
29.	Logistics	(Thomas and Gilbert, 2014)
30.	Inventory	(Thomas and Gilbert, 2014)
31.	New business model	(Thomas and Gilbert, 2014)
32.	Product size	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
33.	Inspection	(Pradel, et al., 2018)
34.	Communication	(Thomas and Gilbert, 2014)
35.	Decentralized production	(Thomas and Gilbert, 2014)
36.	Production on demand	(Thomas and Gilbert, 2014)
37.	Logo information	(Thomas and Gilbert, 2014)
38.	Company image	(Thomas and Gilbert, 2014)
39.	Feature details	(Thomas and Gilbert, 2014)
40.	Light weighting	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
41.	Translation	(Gibson, Rosen and Stucker, 2015; Pradel, et al., 2018)
42.	Customization	(Pradel, et al., 2018)
43.	Functional integration	(Pradel, et al., 2018)
44.	Functionality (end-use)	(Pradel, et al., 2018)
45.	Hardness	(Pradel, et al., 2018)
46.	Density	(Pradel, et al., 2018)
47.	Consumer proximity to production	(ISO/ASTM, 2018; Montero, et al., 2020; Vaneker, et al., 2020)
48.	Energy consumption	(Thomas and Gilbert, 2014)
49.	Recycling	(ISO/ASTM, 2018)
50.	Wastage	(ISO/ASTM, 2018)
51.	Emission	(ISO/ASTM, 2018)
52.	Sustainability	(ISO/ASTM, 2018)
53.	Biodegradable	(ISO/ASTM, 2018)
54.	Radiation exposure ionising	(ISO/ASTM, 2018)
55.	Installation cost	(Montero, et al., 2020)

S.No.	Factors	References
56.	Managerial and production/ manufacturing complexity	(Gibson, Rosen and Stucker, 2015)
57.	Process simplification	(Montero, et al., 2020)
58.	Design changes	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
59.	Internal structures	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
60.	Surface structures	(Pradel, et al., 2018; Vaneker, et al., 2020)
61.	Mathematical expression of the function	(Pradel, et al., 2018; Vaneker, et al., 2020)
62.	Geometry discretization	(Pradel, et al., 2018)
63.	Stiffness	(Pradel, et al., 2018; Vaneker, et al., 2020)
64.	Multi-part mechanism	(Thomas and Gilbert, 2014)
65.	Compliant mechanism	(Montero, et al., 2020)
66.	Operational temperature range	(ISO/ASTM, 2018)
67.	Exposure temperature range	(ISO/ASTM, 2018)
68.	Chemical exposure	(ISO/ASTM, 2018)
69.	Aging of material	(ISO/ASTM, 2018)
70.	Radiation exposure non-ionising	(ISO/ASTM, 2018)
71.	Biological exposure	(ISO/ASTM, 2018)
72.	Readily visible recycling symbol	(ISO/ASTM, 2018)
73.	Reusability	(ISO/ASTM, 2018)
74.	Water consumption	(ISO/ASTM, 2018)
75.	Water stream	(ISO/ASTM, 2018)
76.	Carbon footprint	(ISO/ASTM, 2018)
77.	AM fabrication cost	(ISO/ASTM, 2018)
78.	Total part fabrication cost	(ISO/ASTM, 2018)
79.	Upfront engineering cost	(ISO/ASTM, 2018)
80.	Special packaging and shipping requirements	(ISO/ASTM, 2018; Montero, et al., 2020)

Step 2: Categorization of the factors

Various researchers have tried to classify the factors as per the impact area. One of the categorizations worth mentioning is done by Matthias Schneck and his team, who have clustered the impact factors into four levels of implementation. The first level, known as product, encompasses all the factors that directly benefit AM at the product level. The second level is the process chain, and as the name suggests, this level addresses the benefits to the process chain of the product. The third level, called the life cycle, lists down the factors impacting the life cycle, including the supply chain. Finally, the fourth level, i.e., the company, emphasizes the factors that have influence on the organizational aspects, like the company image and business model (Schneck, et al., 2019).

The ISO/ASTM has laid down a framework for the overall potential analysis for AM, although a clear categorization is not given. The procedure for AM potential identification begins with the identification of material options followed by the identification of build volume. The next step involves identifying a range of potentials, including customization, lightweight design, internal structures or channels, functional integration, designed surface structures, and specific material options. These potentials are placed on the same hierarchy level, and the requirement for proceeding to the next stage is that any one of the mentioned factors would have high or medium potential. If the potential is low, the traditional approach can be considered. The final stage involves considering financial or other business goals before proceeding with AM for the selected object (ISO/ASTM, 2018).

Vaneker and his fellow researchers have developed a framework for AM suitability exploration, in which they have mentioned functional and economical requirements. These two broad categories are carried forward for the feasibility check. Functional requirements are verified by defining AM process chain and AM materials, while economical requirements are checked by conducting cost-benefit analysis by implementing various cost calculation methods (Vaneker et al., 2020).

The identified parameters were categorized into seven domains, viz., machine, material, process, function, design, business, and environment, for streamlining the analysis. These domains were identified by considering all the attempts taken by the researchers and the factors for identification of AM potential. The 80 factors identified in step 1 were clustered into different categories (Table 3).

Table 3: Categorization of attributes

Machine	Material	Process	Function	Design	Business	Environment
Availability	Multi-material	Support structure	All Intended functions	Design complexity	Lead time	Energy consumption
Build volume	Heat dissipation	Simplification of manufacturing	Some additional functions	Design freedom	Production time	Recycling
Envelop utilisation	Thermal conductivity	Process visualisation	Durability	Translation (Design changes)	Production volume	Emission
Product size	Flexural strength	Assembly time		Feature details	Supply chain management	Sustainability
Print time	Tensile strength	Shop floor complexity		Customisation	Vulnerability to supply chain	Material wastage
	Compressive strength	Post processing		Accuracy	Consumer proximity to production	Biodegradable
	SN curve	Surface finish		Precision	Inventory	Radiation
	Melting point	Printing speed		Consolidation	Transportation	Carbon footprint
	Impact strength	Installation		Feature size	Decentralized production	Water consumption
	Hardness	Maintenance		Aesthetic improvement	Batch size	Special packaging and shipping requirements
	Density	Consistency		Functional integration	Logistics	
	Thermodynamic behavior	Non-destructive testing		Decal/ Information	After sales service	
	Young's modulus	Curing/ Finishing			Company image	
	Poisson's ratio				Business case	
	Yield strength				New business model	
	Colour				Production on demand	
	Cost				Communication	
	Availability of material				Fabrication cost	
					Total cost	
					Upfront engineering cost	
5	**17**	**13**	**3**	**12**	**20**	**10**

Step 3: Experts opinion on factors relevant for FDM (Delphi method)

The categorization of the parameters done in step 2 is laid out by the researchers, keeping in mind the general process of AM. However, it is imperative that the weightage of some of the parameters change as per the change in the method of AM. For example, curing time is not relevant for material extrusion, while it is of utmost importance when the object is manufactured through Stereolithography (SLA). Similarly, SLA is known for high accuracy and resolution, and hence it is preferred over material extrusion when it comes to manufacturing small objects like jewellery, which requires high precision (FormLabs, 2021).

Since very little research has been conducted to study the feasibility of FDM considering these parameters, a Delphi study was conducted. A Delphi study is conducted to find a consensus among experts when exact knowledge is not available in the required field. The process can be divided into three stages: 1) Obtaining anonymous responses from the members of the expert panel by circulating a formal questionnaire, 2) Repeating step 1 until a consensus is reached, 3) Statistical analysis of the group response to remove biases (Dalkey, 1969).

As Chitu Okoli and his fellow researchers discussed, the Delphi method has proven its utility and established itself as a popular tool in research studies by obtaining the consensus of an expert group (Okoli and Pawlowski, 2004). To validate the steps of developing the framework for a potential check for FDM, various research papers on the Delphi method were studied in detail. The review paper by McMillan, King, and Tully (2016) explains the process of running the Delphi technique.

The Delphi method has been used by various researchers in different fields like government planning, business and industry, health, manufacturing, information systems, knowledge management, etc., for concept and framework development (Linstone and Turoff, 1975; Nambisan, Agarwal and Tanniru, 1999; Mulligan, 2002; Holsapplea and Joshi, 2002; Kragelj, 2013; Bacon and Fitzgerald, 2001; Schmidt et al., 2001).

A questionnaire was developed to gather expert opinion for finding out the parameters relevant for FDM, or the material extrusion method. Section one contained questions pertaining to the general information of the experts, like designation, organization, and level of awareness of AM and its seven methods as per the ASTM F42 technical committee (ISO/ASTM 52900:2021(en), 2021).

The second part consisted of seven main questions with each factor and their respective parameters covering the entire 80 parameters, which were identified from the literature review. The questions were designed on a Likert scale based on feasibility importance with the following ratings as shown in Table 4.

Table 4: Scale development

S.No.	Importance scale	Ratings
1	Not at all important	1
2	Somewhat important	2
3	Neutral	3
4	Very important	4
5	Extremely important	5

Sampling frame and adequacy of factor analysis

The expert panel comprised 15 experts with varied profiles, like academics, researchers, and industry professionals. The names are not disclosed due to confidentiality reasons; however, the profiles are mentioned in Table 5. The experts demonstrated adequate experience in the field of additive manufacturing, especially in fused deposition modeling. The experts belonged to different domains to ensure sufficient diversity and get suitable responses from across all the fields. The sampling technique in identifying the sample was purposive sampling, which is a non-probability technique where the participants are selected intentionally as per the relevance to the study.

For exploratory factor analysis, while larger sample sizes are preferred, some researchers like Hinkin (1995) and Costello (2005) have confirmed that in the case of higher communalities and stronger factor loading, small sample sizes are relevant too. In this research paper smaller sample sizes are justified as the factor loading values range from -0.854 to 0.960.

Table 5: Profiles of Delphi experts

S.No.	Designation	Organization	Experience	Profile
1.	Application Manager	Phillips	Expert	Industry
2.	Assistant Professor	Erode Sengunthar Engineering College	Proficient	Academics
3.	Regional Manager - Sales	Imaginarium Solutions (I) Pvt. Ltd.	Expert	Industry
4.	Research Scholar	NIT, Warangal	Proficient	Researcher
5.	Research Scholar	Vellore Institute of Technology	Proficient	Researcher

S.No.	Designation	Organization	Experience	Profile
6.	Assistant Professor	Bannari Amman Institute of Technology	Expert	Academics
7.	Assistant Professor	NIFT Patna	Expert	Academics
8.	Deputy Manager	Forza Medi (India) Pvt. Ltd.	Expert	Industry
9.	Professor	NIFT, Varanasi	Proficient	Academics
10.	6 Sigma Head	Indium	Expert	Industry
11.	Technology Manager	Vfuse Metal 4 Manufacturing Pvt. Ltd.	Proficient	Industry
12.	Assistant Professor	NIFT, Kolkata	Expert	Academics
13.	Technical Manager	WOL3D India Ltd.	Expert	Industry
14.	Technical Manager	WOL3D India Ltd.	Expert	Industry
15.	Research Scholar	Anna University	Proficient	Researcher

The responses were recorded and coded as per the attributes listed in Table 1. The mean for each parameter was calculated. Subsequently, the mean of all the means was calculated, which resulted in 3.864198. The responses with the mean rating less than the total mean, i.e., 3.864198, were dropped from subsequent steps (Table 6). Along with the mean ratings, the standard deviations were also calculated to understand the variation in the responses of the experts. Most of the retained parameters exhibited low standard deviation values, showing a strong consensus among panel members. For selected parameters, the SD values ranged from 0.3 to 0.6. Following analysis of the responses from the Delphi method (Table 7), 42 parameters were selected and taken forward for factor analysis.

Table 6: Selection of parameters based on Delphi response

S.No.	Factors	Parameters	Ratings	Selected/ Dropped
1.	Design	Design complexity	4.4000	Selected
2.		Design freedom	4.2667	Selected
3.		Translation (Design changes)	4.3333	Selected
4.		Feature details	3.8000	Dropped
5.		Customisation	4.4000	Selected
6.		Accuracy	4.0667	Selected
7.		Precision	3.8667	Selected
8.		Consolidation	4.0667	Selected
9.		Feature size	3.8667	Selected

S.No.	Factors	Parameters	Ratings	Selected/ Dropped
10.		Aesthetic improvement	3.9333	Selected
11.		Functional integration	3.8667	Selected
12.		Decal/Information	3.7333	Dropped
13.	Machine	Availability	3.6667	Dropped
14.		Build volume	4.2000	Selected
15.		Envelop utilisation	3.5333	Dropped
16.		Product size	3.8667	Selected
17.		Print time	4.4667	Selected
18.	Process	Support structure	4.5333	Selected
19.		Simplification of manufacturing	4.1333	Selected
20.		Process visualisation	3.4667	Dropped
21.		Assembly time	3.4667	Dropped
22.		Shop floor complexity	3.3333	Dropped
23.		Post processing	4.0667	Selected
24.		Surface finish	4.7333	Selected
25.		Printing speed	4.5333	Selected
26.		Installation	3.6667	Dropped
27.		Maintenance	3.7333	Dropped
28.		Consistency	4.0667	Selected
29.		Non-destructive testing	3.2000	Dropped
30.		Curing/Finishing	3.9333	Selected
31.	Business	Lead time	3.9333	Selected
32.		Production time	4.3333	Selected
33.		Production volume	3.8000	Dropped
34.		Supply chain management	3.8000	Dropped
35.		Vulnerability to supply chain	3.4667	Dropped
36.		Consumer proximity to production	3.7333	Dropped
37.		Inventory	3.8000	Dropped
38.		Transportation	3.6667	Dropped
39.		Decentralized production	3.5333	Dropped
40.		Batch size	3.6667	Dropped
41.		Logistics	3.3333	Dropped
42.		After sales service	3.3333	Dropped
43.		Company image	3.4000	Dropped
44.		Business case	3.4000	Dropped
45.		New business model	3.2000	Dropped

S.No.	Factors	Parameters	Ratings	Selected/ Dropped
46.		Production on demand	3.8000	Dropped
47.		Communication	3.2667	Dropped
48.		Fabrication cost	4.2000	Selected
49.		Total cost	3.9333	Selected
50.		Upfront engineering cost	3.6667	Dropped
51.	Environmental	Energy consumption	4.3333	Selected
52.		Recycling	3.4667	Dropped
53.		Emission	3.6667	Dropped
54.		Sustainability	3.8667	Selected
55.		Material wastage	4.1333	Selected
56.		Biodegradable	3.7333	Dropped
57.		Radiation	3.2667	Dropped
58.		Carbon footprint	3.5333	Dropped
59.		Water consumption	2.8667	Dropped
60.		Special packaging and shipping requirements	3.2000	Dropped
61.	Functional	All intended functions	4.0000	Selected
62.		Some additional functions	3.6667	Dropped
63.		Durability	4.2000	Selected
64.	Material	Multi-material	3.4667	Dropped
65.		Heat dissipation	3.3333	Dropped
66.		Thermal conductivity	3.4667	Dropped
67.		Flexural strength	4.0000	Selected
68.		Tensile strength	4.3333	Selected
69.		Compressive strength	4.4000	Selected
70.		SN curve	4.4000	Selected
71.		Melting point	4.0667	Selected
71.		Impact strength	4.3333	Selected
72.		Hardness	4.1333	Selected
73.		Density	4.1333	Selected
74.		Thermodynamic behavior	3.8000	Dropped
75.		Young’s modulus	4.2667	Selected
76.		Poisson’s ratio	4.2000	Selected
77.		Yield strength	4.3333	Selected
78.		Colour	3.0667	Dropped
79.		Cost	4.5333	Selected
80.		Availability of material	4.3333	Selected

Step 4: Factor analysis and final categorization

For further study, the structure and relevance of the parameters selected from the Delphi responses were subjected to factor analysis. Factor analysis was performed with three basic objectives: 1) to determine the number and nature of the variables. 2) to determine the influence of common factors on the attributes. 3) to analyse the inter correlation among the variables and determine common factors (Tucker and MacCallum, 1997).

IBM SPSS Statistics was used to perform Exploratory Factor Analysis (EFA), as presented in Table 7. The Varimax rotation method was used in SPSS, and the extraction method used was Principal Component Analysis. The rotation converged in 24 iterations. The minimum loading value was -0.854, while the maximum loading value was 0.960. There is no clear recommended cut-off for the loading value, but usually researchers have considered 0.4 as a suitable cut-off (Hinkin, 1995). 0.3 has also been proposed by many researchers (Costello and Osborne, 2014). As the values below 0.3 are considered insignificant, the attributes with a loading value below 0.3 were discarded. A total of 7 factors were identified, and the attributes were grouped based on higher loading value (Phogat and Gupta, 2019).

Table 7: Exploratory Factor Analysis

Rotated Component Matrix[a]										
Rate the following design parameters in response to its importance towards FDM feasibility:	**Component**									
	1	2	3	4	5	6	7	8	9	10
Design complexity	0.375	-0.168	0.172	-0.466	0.592	-0.284	0.077	0.296	-0.134	0.063
Design freedom	0.357	0.535	0.061	0.269	0.145	-0.030	-0.295	-0.350	-0.498	-0.033
Translation (Design changes)	0.055	0.163	0.321	-0.095	0.675	0.030	0.036	-0.332	0.255	-0.390
Customisation	0.179	-0.316	0.010	0.213	0.730	0.321	0.068	-0.298	0.048	0.102
Accuracy	-0.061	0.315	0.303	0.029	0.743	0.286	0.054	-0.169	0.025	0.291
Precision	-0.613	0.334	0.223	0.046	0.461	-0.105	-0.303	-0.206	-0.174	-0.055
Consolidation	-0.254	0.298	-0.075	0.116	0.716	-0.208	-0.231	-0.044	0.396	-0.067
Feature size	-0.178	0.148	-0.096	0.448	0.660	-0.217	-0.358	0.226	-0.012	-0.063
Aesthetic improvement	-0.804	0.098	0.177	0.358	-0.143	0.162	-0.130	-0.044	0.162	-0.053
Functional integration	-0.607	0.201	0.286	0.535	0.112	0.308	-0.017	0.051	0.154	0.108
Build volume	-0.167	-0.200	0.089	0.044	-0.006	-0.020	0.678	0.095	0.014	0.624
Product size	0.113	0.090	0.033	0.130	0.121	-0.854	0.276	-0.151	-0.142	0.291

Print time	0.240	-0.115	0.181	-0.191	0.103	-0.094	0.225	-0.088	0.234	0.823
Support structure	0.117	-0.146	0.684	0.276	-0.073	-0.034	0.124	0.535	-0.050	0.180
Simplification of manufacturing	-0.433	-0.177	0.807	0.000	0.161	0.035	-0.143	0.118	0.032	0.057
Post processing	-0.271	0.036	0.763	0.366	0.062	-0.041	0.302	-0.039	0.203	0.021
Surface finish	0.176	0.004	0.880	0.079	0.173	-0.132	0.126	0.064	-0.063	-0.003
Printing speed	0.019	0.414	0.353	-0.284	0.099	0.063	-0.220	0.639	-0.125	0.363
Consistency	-0.543	-0.113	0.087	0.704	0.169	0.099	0.189	-0.015	0.290	-0.121
Curing/ Finishing	-0.302	0.075	0.194	0.826	0.176	-0.222	0.091	0.005	-0.208	-0.025
Lead time	-0.133	-0.126	0.059	0.061	-0.189	0.124	0.007	0.907	-0.011	-0.154
Production time	0.275	-0.560	0.383	-0.057	0.088	0.131	0.209	0.534	0.054	0.040
Fabrication cost	0.379	0.060	0.450	0.005	0.182	0.354	0.592	-0.053	-0.175	-0.033
Total cost	-0.578	0.180	0.228	0.558	0.168	0.100	0.352	0.193	-0.212	-0.036
Energy consumption	-0.231	-0.140	0.087	0.333	0.598	0.151	-0.136	0.393	-0.227	0.368
Sustainability	-0.473	0.194	0.045	0.544	0.006	0.131	0.510	0.076	-0.305	-0.144
Material wastage	-0.056	-0.050	0.083	0.108	-0.199	0.080	0.925	-0.038	0.174	0.146
All Intended functions	0.295	0.003	-0.046	0.034	0.203	0.866	0.287	-0.019	-0.143	-0.006
Durability	0.205	0.024	-0.092	0.210	0.005	0.850	0.229	0.106	-0.099	0.191
Flexural strength	0.160	0.008	0.493	0.693	-0.020	0.246	-0.109	-0.092	-0.254	-0.014
Tensile strength	0.934	0.068	-0.037	-0.096	0.028	0.112	0.137	-0.057	-0.104	0.186
Compressive strength	0.896	0.146	0.096	0.005	0.113	0.175	-0.119	-0.060	-0.033	0.184
SN curve	0.839	0.285	-0.119	0.160	0.042	-0.095	-0.331	0.016	0.021	-0.009
Melting point	0.088	0.960	0.052	0.008	-0.059	-0.002	-0.014	0.046	0.173	-0.098
Impact strength	0.389	0.872	0.047	-0.020	0.159	0.154	-0.040	-0.147	0.003	-0.072
Hardness	0.134	0.912	-0.163	0.161	0.168	-0.006	-0.065	0.007	-0.193	-0.030
Density	0.225	0.680	0.073	-0.087	-0.073	-0.369	0.293	-0.029	0.479	0.112
Young's modulus	0.909	0.282	0.027	-0.132	-0.073	0.128	0.008	-0.060	-0.091	-0.075
Poisson ratio	0.783	0.208	0.125	-0.280	-0.233	0.271	-0.032	0.118	0.156	-0.215
Yield strength	0.716	0.299	0.074	-0.281	-0.111	0.399	0.104	-0.129	0.098	-0.221
Cost	-0.064	0.055	0.072	-0.099	0.160	-0.015	0.032	-0.089	0.951	0.103
Availability of material	-0.104	0.418	0.629	0.125	-0.079	-0.210	0.061	0.146	0.371	0.392
Extraction Method: Principal Component Analysis. Rotation Method: Varimax without Kaiser Normalization.[a]										
a. Rotation converged in 24 iterations.										

The number of factors was retained based on the criterion that the eigenvalue >= 1. This requirement is also known as Kaiser's rule and is usually used in defining the threshold for extracting the factors. This rule states that only factors that have an eigenvalue greater than or equal to 1 should be retained. This is because they explain more variance (Hinkin, 1995). Along with the eigenvalues, the convergence and high factor loading also validate the data suitability.

Although EFA is a statistical method that defines the relationship between factors and attributes, it is known to have some amount of subjectivity, by virtue of which the researcher is endowed with the freedom to group two or more similar factors together. This leads to a shorter scale, thereby reducing complexity in subsequent steps (Maskey, Fei and Nguyen, 2018; Goretzko, Pham and Bühner, 2019). The result is tabulated in Table 8.

Table 8: Final factors

Process	**Machine**	**Material**	**Functional**	**Design**	**Business**	**Environment**
Support structure	Design Freedom	Hardness	Functional integration	Design complexity	Fabrication cost	Printing speed
Curing/ Finishing	Build volume	Impact strength	All functions	Translation (Design changes)	Total cost	Lead time
Consistency		Melting point	Durability	Customization	Simplification of manufacturing process	Production time
Post processing		Tensile strength		Accuracy		Sustainability
		Material availability		Precision		Material wastage
		Density		Consolidation		Energy consumption
		Compressive strength		Feature size		
		SN Curve		Surface finish		
		Young's modulus				
		Poisson's ratio				
		Yield strength				
		Flexural strength				

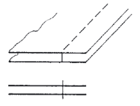
Step 5: Development of a framework for assessment of the potential for FDM

Based on the final factors identified after factor analysis and prioritization of the factors, a framework was developed for the assessment of manufacturability feasibility by FDM, a method of AM, as shown in Figure 6.

The first step is part selection using a preliminary study in which function, feature, and performance studies are performed. The findings are recorded in a data sheet. An example data sheet is given in Figure 5.

General Information	
Part name	Spring hinged presser foot
Category	Industrial single needle lock stitch basic hinged non-compensating
Description	Standard Spring hinged twin toe presser foot
Application	For joining two plies of fabric by an industrial SNLS machine
Material	Stainless steel
Dimension mm	35x35x7
Weight g	50

Seam Diagram 1



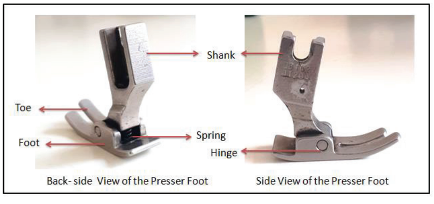
Seam properties	
Fabric	100% cotton
Fabric GSM	150
No. of plies	2-4
SPI	10-12
Stitch number	301
Thread ticket	120
Machine RPM	3000
Force applied	15-40 N
Seam type	Superimposed

Seam Diagram 2

Mechanical Properties	
Density	8.00 g/cm^3
Melting Point	1400°C
Modulus of Elasticity	193 GPa
Tensile Strength (MPa)	500 - 700
Proof Stress (MPa)	200 Min
Elongation A50 mm	40 Min %
Hardness Brinell	215 Max HB

Seam Diagram 3

Part Diagram/ Image



Additional Notes and Remarks

Created by: Created on: Signature

Figure 5: Sewing machine spare parts data sheet

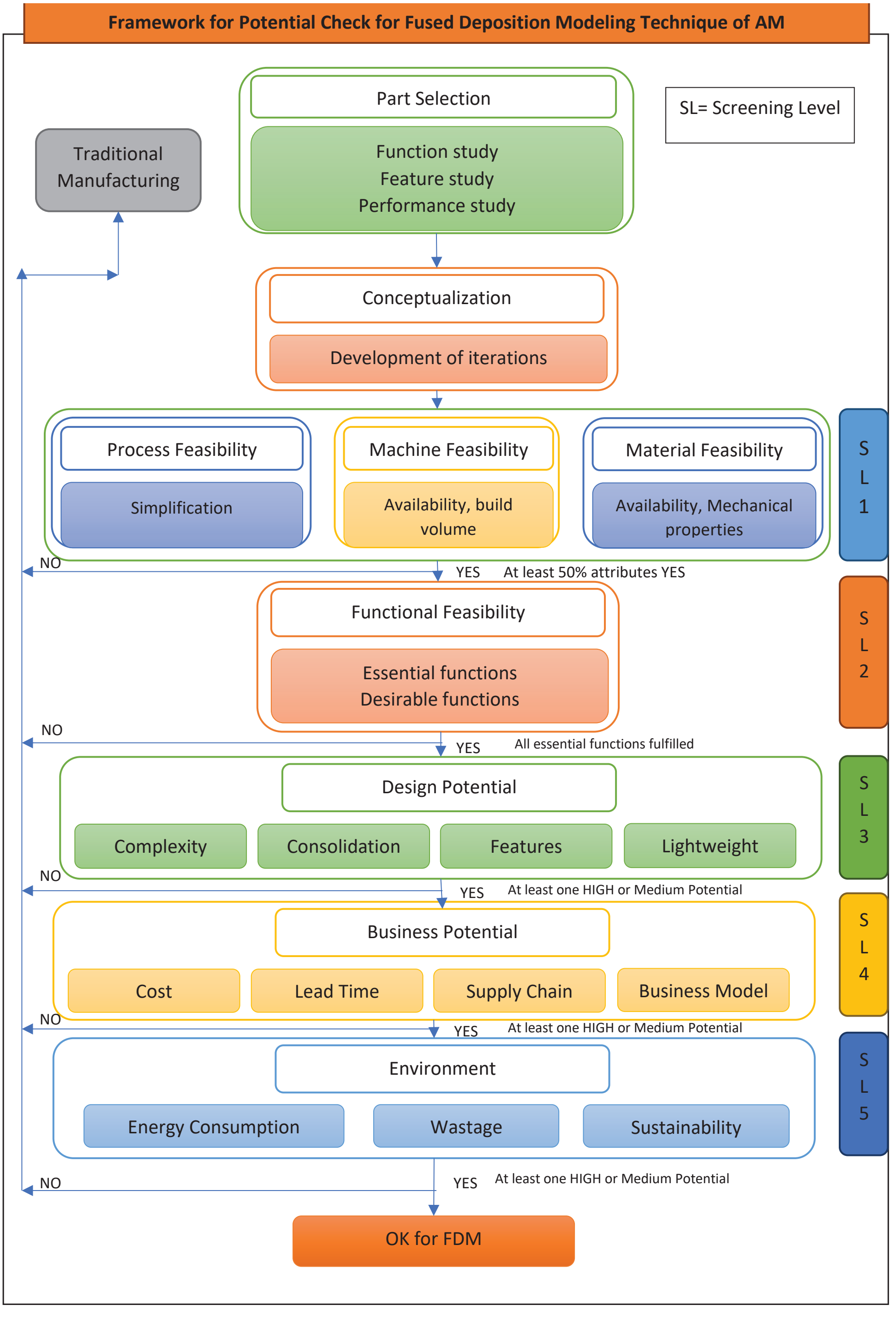


Figure 6: Framework for manufacturability assessment by FDM

The second step, according to the framework, is conceptualization, i.e., considering the functionality, available and compatible materials, assembly, etc. The basic shape needs to be identified and checked for the basic intended functions. The subsequent step is divided into five screening levels.

The screening framework is divided into five levels. The first level of screening consists of process feasibility, which focuses on the simplification of the manufacturing process; machine feasibility, which determines the availability and build volume of the printer; and material feasibility, which determines the availability of the material and its mechanical properties. The screening process advances to level 2 if the object achieves a score of at least 50 percent in level 1.

Level 2 of the screening assesses functional feasibility by studying how the additively manufactured object performs for both essential and desirable functions. If the essential functions are fulfilled by the object, then the design potential is analyzed in screening level 3, which consists of the design complexity of the object, part consolidation, number of small features, and the lightness of the part.

To qualify for screening level 4, at least one factor in screening level 3 needs to be high or medium. Screening level 4 checks the potential of the object from a business perspective. The factors like cost, lead time, supply chain, business model, and scalability are considered for the same. Again, at least one factor needs to be high or medium potential for the object to qualify for the last screening level, i.e., level 5.

Screening level 5 concerns the environmental aspects. The factors considered for this level are energy consumption, wastage, and sustainability. If at least one of the factors in screening level 5 scores high or medium potential, then the part qualifies for being manufactured by the FDM method of AM. If the object fails on any level, then the traditional method of manufacturing may be preferred.

Conclusion and Future Scope

The framework developed is exhaustive, as maximum numbers of attributes are considered from secondary literature, and the attributes that are relevant for fused deposition modelling (FDM) are retained by a systematic approach. The approach includes the inputs of the experts in the field of additive manufacturing, particularly FDM.

The framework can be incorporated in a garment factory during the early stages of developing a product that would aid in the production of a garment order. If there is a requirement of a specific work aid that is crucial for executing a garment order, it could be either manufactured in-house using an FDM setup, or it could be procured from a place where it is manufactured using a traditional method. However, even though the FDM provides immense benefits like drastically shorter lead time and cost savings, sometimes it is not feasible for the product to be manufactured by FDM because of reasons like material feasibility or certain geometrical limitations. Thereby, it becomes important that the manufacturability analysis for the work aid or other spare parts is done beforehand to take an informed decision to avoid the chances of failure.

The framework, which includes technical, functional, design, business, and environmental factors, serves as a well-structured decision-making tool with a five-level screening model. It is helpful for the manufacturers to evaluate the manufacturability of a component with respect to FDM and make informed decisions. It has strong potential for practical applications in the garment industry as well as for manufacturing small parts. This framework aligns with Industry 4.0 by promoting decentralization, on-demand production, and sustainability.

The future scope of this framework is to implement it in the garment manufacturing industry. This framework will be useful to analyze the feasibility of manufacturing sewing machine spare parts in-house using the fused deposition modeling technique of additive manufacturing. This study would become an integral part of the adoption of a new business model, which would greatly curtail the supply chain, thereby providing a competitive edge in the industry.

References

ISO/ASTM 52900:2021(en), 2021. *Additive manufacturing — General principles — Fundamentals and vocabulary.* [Online] Available at: <https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-2:v1:en> [Accessed 5 April 2022].

Bacon, C.J., Fitzgerald, B., 2001. A Systemic framework for the field of information systems. *The DATA BASE for Advances in Information Systems,* 32(2), pp.46-67.

Costello, A.B. and Osborne, J., 2005. Best practices in exploratory factor analysis: four recommendations for getting the most from your analysis. *Practical Assessment, Research and Evaluation,* 10(7), pp.1-9.

Costello, A. and Osborne, J., 2014. *Best practices in exploratory factor analysis.* 1 ed. CA: CreateSpace Independent Publising.

Dalkey, N.C., 1969. *The delphi method: an experimental study of group opinion.* 1sted. California: The Rand Corporation.

FormLabs, 2021. *FDM vs. SLA vs. SLS: 3D printing technology comparison.* [Online] Available at: <https://formlabs.com/asia/blog/fdm-vs-sla-vs-sls-how-to-choose-the-right-

3d-printing-technology/?srsltid=AfmBOop4ecxS26JqA_UsHoXoOBK_PcCIg4Qgm-LdbFy_A7nL1wlzL6_J> [Accessed 29 March 2022].

Gibson, I., Rosen, D. and Stucker, B., 2015. *Additive manufacturing technologies.* 2nd ed. New York: Springer.

Goretzko, D., Pham, T.T.H. and Bühner, M., 2019. Exploratory factor analysis: current use, methodological developments and recommendations for good practice. *Current Psychology,* 40, p.3510–3521.

Hague, R., Mansour, S. and Saleh, N., 2003. Design opportunities with rapid manufacturing. *Assembly Automation,* 23(4), pp.346–356.

Hinkin, T.R., 1995. A review of scale development practices in the study of organisation. *Journal of management,* 21(5), pp.967-988.

Holsapplea, C.W. and Joshi, K.D., 2002. Knowledge manipulation activities: results of a delphi study. *Information & Management ,* 39(6), p.477–490.

ISO/ASTM, 2018. *Additive manufacturing — Design — Requirements, guidelines and recommendations,* pp.1-15.

Montero, J., Weber, S., Bleckmann, M. and Paetzold, K., 2020. Re-Design of Additive Manufactured Spare parts Based on Features Classification. *Proceedings of the DESIGN 2020 16th International Design Conference,* 11th June 2020: Cambridge University Press.

Kragelj, G.B. and L.Z., 2013. *Health investigation: analysis- planning- evaluation.* 1st ed. Hellweg: Jacobs Publishing Company.

Kumke, M., Watschke, H. and Vietor, T., 2016. A new methodological framework for design for additive manufacturing. *Virtual and Physical Prototyping,* 11(1), pp.3-19.

Linstone, H.A. and Turoff, M., 1975.*The delphi method, techniques and applications.* 1st ed. California: Murray Turoff and Harold A. Linstone .

Lipson, H. and Kurman, M., 2018. *Fabricated: the new world of 3d printing.* Indianapolis: John Wiley & Sons, Inc.

Maskey, R., Fei, J. and Nguyen, H-O., 2018. Use of exploratory factor analysis in maritime research. *The Asian Journal of Shipping and Logistics,* 34(2), pp.91-111.

McMillan, S.S., King, M. and Tully, M.P., 2016. How to use the nominal group and delphi techniques. *Int J Clin Pharm,* 38, pp.655–662.

Mulligan, P., 2002. Specification of a capability based IT classification framework. *Information and Management,* 39(8), pp.647-658.

Nambisan, S., Agarwal, R. and Tanniru, M., 1999. Organizational mechanisms for enhancing user innovation in information technology. *MIS Quaterly,* 23(3), pp.365-395.

Okoli, C. and Pawlowski, S.D., 2004. The Delphi Method as a research tool:an example, design considerations and applications. *Information & Management,* 42(1), pp.15-29.

Phogat, S. and Gupta, A.K., 2019. Evaluating the elements of just in time (JIT) for implementation in maintenance by exploratory and confirmatory factor analysis. *International Journal of Quality & Reliability Management,* 36(1), pp.7-24.

Pradel, P., Zhu, Z., Bibb, R. and Moultrie, J., 2018. Investigation of design for additive manufacturing in professional design practice. *Journal of Engineering Design,* 29(4-5) pp.1-36.

Schmidt, R., Lyytinen, K., Keil, M. and Cule, P., 2001. Identifying software project risks: an international delphi study. *Journal of Management Information Systems,* 17(4), pp.5-36.

Schneck, M., Gollnau, M., Lutter-Günther, M., Haller, B., Schlick, G., Lakomiec, M. and Reinhart, G.,2019. Evaluating the use of additive manufacturing in industry applications. *Procedia CIRP,* 18*,* pp.19-23.

Thomas, D.S. and Gilbert, S.W., 2014. Costs and cost effectiveness of additive manufacturing. *Special Publication (NIST SP),* [pdf] Available at: <https://nvlpubs.nist.gov/nistpubs/specialpublications/nist.sp.1176.pdf> [Accessed July 2025].

Tucker, L.R., and MacCallum, R.C., 1997. *Exploratory factor analysis.* 1sted. Illinois: s.n.

Vaneker, T., Bernard, A., Moroni, G., Gibson, I., and Zhang, Y., 2020. Design for additive manufacturing: framework and methodology. *CIRP Annals - Manufacturing Technology,* 69(2) pp.578-599.

About the authors

Abhilasha Singh is Assistant Professor in the Department of Fashion Technology, NIFT, Patna. She is currently pursuing her Ph.D. in the area of additive manufacturing from NIFT. She is a NIFT Delhi and Gandhinagar alumnus, with over five years of industry experience before joining NIFT as faculty. A keen interest in research and development has led her to take and complete various research projects of national and international repute. Her paper presented at QUT, Australia, on Automatic Seam Ripping System (ASRS) was recognized globally and applauded by the Confederation of Indian Textile Industry (CITI). She holds seven patents and has published 13 research papers in international journals and conferences. Her research interests include additive manufacturing, textiles, supply chain and merchandising, pattern making, garment construction, and education.

abhilasha.abhilasha@nift.ac.in

Prabir Jana, a visionary in the development, application, and management of technology in apparel manufacturing, started his professional career with a private garment manufacturing enterprise in 1991. After a brief stint with manufacturing and buying organizations, he joined the NIFT Delhi. Currently he is the Shahi Chair Professor of Industry 4.0 at NIFT, Delhi. During his 30+ illustrious years at NIFT, he has served as Chairperson of the Department of Fashion Technology, Head of Industry Linkages, Head of Information Technology, and Head of Research. His special research interests include technology improvisation, sewing automation, industrial engineering, ergonomics, 3D printing, and smart garments. A prolific contributor for technology columns in various journals, he has written over 300 articles, edited and authored 15 books, and filed 5 patents. Prabir Jana is a graduate in Textile Technology from Calcutta University, a postgraduate in Garment Manufacturing Technology from NIFT, New Delhi, and a PhD from Nottingham Trent University, UK.

prabir.jana@nift.ac.in

Deepak Panghal is a seasoned academic and industry professional specializing in mechatronics, Industry 4.0, and low-cost automation systems. With over 18 years of experience, he serves as a faculty member at NIFT, New Delhi, and is the co-founder of Apparel 4.0 Technologies Pvt. Ltd., a start-up that has received prestigious accolades like the H&M Global Innovation Award and ITMA Startup Valley Award. Deepak holds a PhD in mechanical engineering and has developed innovative solutions for the apparel manufacturing industry. The University of Canterbury, New Zealand, recently awarded him the prestigious Erskine Fellowship, acknowledging his contributions to both academia and industry. With 3 granted patents, 4 under examination, and research projects worth approximately ₹10 million, he has a robust portfolio of impactful work. An accomplished author, he has numerous high-impact journal publications and book chapters. He has also established advanced labs at NIFT, guided postgraduate and doctoral students, and integrated cutting-edge research with practical industry applications globally.

deepak.panghal@nift.ac.in.

Tactile and Visual Sensory-Based Adaptive Functional Clothing for Children with Autism Spectrum Disorder

Tulika Saikia, Sandip Mukherjee and Dalia Nandi

Abstract

Autistic children belong to a sect of the population that is usually ignored in design, especially to prepare them for the challenges and problems they will face in everyday life. Children with autism are more sensitive to their physical surroundings than the average person, which often leads to them feeling overwhelmed by the environment. This syndrome is primarily due to sensory processing deficits, which create challenges in understanding and adapting to the environment, resulting in anxiety. Emotional and behavioral issues frequently co-occur at a higher prevalence in children with autism compared to typical controls, which often disrupts intervention efforts and exacerbates functional impairment, parental distress, parent-child relationships, and the health-related quality of life for caregivers.

In recent years, with the evolutionary segment of the technical textiles market, clothing has crossed conventional boundaries to integrate various domains like medicine, biotechnology, nanotechnology, etc. with design. Functional clothing exemplifies apparel design that consistently aligns harmoniously with individuals having specific needs. Due to the wide variety of fibers, yarns, fabrics, and manufacturing techniques available for producing products tailored to specific end-use applications, it offers unparalleled versatility in system design. Textile becomes an optimal medium for information processing, as it possesses the potential to incorporate redundancies for fault tolerance.

This research article demonstrates the integration of functional clothing with electronic sensory designs, both tactile and visual, to help children with autism cope effectively with and adjust to change. The ability of this garment to gather data from the user or its surroundings and utilize that input to activate or modify the state of an attached technology makes this garment different from other types of clothing. The number of sensors and their ability to sense context, process information, and effectuate changes

determine how intelligent a garment is. The study highlights the dearth of design considerations for children with autism spectrum disorders and awakens the urgent need for sensory textiles in functional apparel to help autistic children.

Keywords: Autistic children, functional clothing, sensory mechanism, interactive design, tactile and visual experience

Introduction

The term 'Autism Spectrum Disorder' (ASD) refers to a group of conditions that are characterized by challenges with speech and nonverbal communication, repetitive activities, social skills, and distinctive strengths and traits (Yates, 2016). It is classified under the category of Neurodevelopmental Disorder (NDD), which is defined as a category of conditions that manifest during the developmental stage and cause deficiencies that eventually lead to functional impairments. Assimilation and processing information from various environmental sources are often challenging for people with autism. They may be overly sensitive, completely devoid of senses, or both. Other additional characteristics of ASD include atypical patterns of behavior and activity, such as difficulty switching between activities, attention to details, and unusual reactions to sensations (World Health Organization, 2023). While some children with ASD may have a decreased sensitivity level, others may be more sensitive than typical to environmental stimuli like noise, light, clothing, etc.

Children with ASD may experience severe challenges as a result of unpredictable changes in schedules and routine (Cañete and Peralta, 2022). They often display anxiety, lack of motivation and attention, and abnormal responses to various stimuli, which makes them different from their peers (Chakrabarty, 2019). Speech is either delayed or predominantly absent. It leads to deficiencies or departures from normative development in the three main domains, i.e., social cognition, communication, and imaginative capacity, particularly in social imagination. People with autism exhibit atypical responses to sensory stimuli. Individuals with autism may display impairments in one or more senses. These difficulties may manifest in their behavior, causing individuals with autism to engage with others, objects, and events in their environment in unusual ways. Autistic children may exhibit a wide range of symptoms or characteristics, from mild to severe, making it a spectrum condition (Willis, 2006). As a result of these social challenges, children with ASD are vulnerable to social rejection and isolation (Douglas et al., 2022). Delays in communication and social interaction, obsessions with particular objects, repetitive body motions, and obsessively following specialized routines and rituals are all characteristics of ASD (Kommu, 2011). The symptoms of ASD typically occur in the age group of two to three years old (Wright and Wright, 2005). In certain situations, it can be identified as early as 18 months (Perrin and Coury, 2012).

The type and characteristics of ASD make it a very complex disorder. There are five types of ASD. Kanner's Syndrome, also referred to as the classic autistic condition, includes uncontrollable speech, an obsession with handling objects, and an inability to form emotional bonds with others. The individual demonstrates advanced abilities in rote memory and visuospatial skills but experiences challenges in interpersonal interaction and communication. They also struggle a lot in different areas of learning and education (Sruthi, n.d.) Children with Pervasive Developmental Disorder Not Otherwise Specified (PDDNOS), a type of autism in which their traits are different from those of other autistic children and are typically diagnosed after the age of three. PDDNOS is characterized by significant challenges in social and language development, and it can coexist with a wide range of intellectual abilities, like other forms of autism (Autism Speaks, n.d.). Children having Asperger's Syndrome develop social skills and communication like adolescents, but they struggle with coordination, vocal intonation, depression, violent reactions to change, and a proclivity for ritualistic behavior (Mikami and Matsumoto, 2007). Rett Syndrome is a distinct neurodevelopmental condition that primarily affects girls and is initially identified in infancy (Indian Rett Syndrome Foundation, n.d.). This syndrome causes severe impairments in almost every aspect of a child's life. Common symptoms of Rett syndrome encompass diminished mobility or abnormalities in walking, decreased muscle tone, microcephaly (reduced head size), impaired speech, loss of hand functionality, involuntary hand movements, seizures, breathing difficulties, sleep disturbances, and scoliosis (abnormal spinal curvature). Childhood Disintegrative Disorder (CDD) is characterized by the disintegration of mental function and the regression of acquired language and intellectual skills in a child following a period of normal development (Verma and Mohapatra, 2016). After two years of normal growth and development, the child may start to show signs of CDD. This condition usually manifests between the ages of three and four, but it can occur at any time before the child turns ten (Sruthi, n.d.). The initiation of CDD could occur all at once or over time. Children might possess an understanding of what's going on with them and inquire about the nature of their illness. Parents or experts might fail to notice developmental changes in areas such as the child's language, communication, social relationships, and emotional development (Kommu, 2011). Children may experience hallucinations, which are when they see, hear, or smell things that do not actually exist (Sruthi, n.d.). A child who used to be able to talk in two or three sentences may experience a progressive cessation of speech. A child who used to enjoy affectionate embraces may now be very against any kind of physical contact.

Sensory processing and autistic children

Sensory processing denotes the capacity to assimilate information from the environment and the body, evaluate its significance, and arrange it into motor and social responses (Chakrabarty, 2019). An individual constantly learns and perpetually acquires knowledge about their surroundings through their senses. Sensory processing impairment is common in children with autism and other forms of ASD, along with emotional and behavioral problems (Tseng et al., 2011). Sensory processing includes reception, change, integration, and organization of sensory information, along with the behavioral reaction of people to such information. The neurological system's ability to adjust input partially determines how a person reacts to different types and amounts of sensory stimuli. The nervous system works rapidly when sensory input is appropriately regulated or controlled. It makes precise assessments about input and changes the nervous system's arousal state to prepare it ready for action. Children with sensory processing impairments may have trouble in understanding and interpreting what they see, hear, and feel, which can slow down their fine motor skills development. Individuals with a sensory processing disorder have challenges regulating and organizing their behavioral responses to sensory stimuli in a way that fits the needs of their environment.

Children with ASD have unusual sensory reactions ranging from hyper-responsiveness to hypo-responsiveness (Kyriacou, Forrester-Jones and Triantafyllopoulou, 2021), which interferes with their daily life. Hyper-responsiveness refers to the sensory channel being too open, allowing too much stimulus into the brain, whereas hypo-responsiveness refers to the sensory channel being too closed, allowing too little stimulation into the brain and depriving it of sensory input (Ghazali, Sakip, and Samsuddin, 2018). Since autistic children are more sensitive to their physical environment, they react to sensory inputs with conduct that is not proportional to the degree and kind of the sensory stimulation. When an autistic child is unable to comprehend or adjust to their surroundings, unacceptable behavior ensues, resulting in significant levels of anxiety, stress, and confusion. In addition, the challenges they pose in terms of planning and organizing abilities result in reduced self-autonomy and an incapacity to self-manage.

Children having autism sometimes exhibit severe symptoms of anxiety (South and Rodgers, 2017). The sensory-based anxiety subscale, along with the subscales for performance-related anxiety and challenges with uncertainty, plays an important role. Because of this, individuals with autism may display sensory soothing behavior that repeats or makes sensory experiences stronger. Sensory soothing behavior needs strong sensory inputs to produce a calming response. Different responses to a variety of input modalities like taste, smell, sound, sight, and touch have been found in autistic children. This implies that a "one size fits all" approach to design is not right for every autistic child. Sensory-based interventions are frequently employed to address behaviors in autistic children impacted by sensory processing difficulties (Case-Smith, Weaver and Fristad, 2015). Sensory-based intervention may include weighted blankets, weighted vests, and sensory clothing to help with sensory processing variations. To enhance the sensory experience in functional clothing, two of the senses, touch and sight, are heavily focused upon. Children with autism are often diagnosed to be more sensitive towards sensory inputs like touch, hearing, and sight (Grandgeorge and Masataka, 2016). They often depend on visual stimuli to understand their surroundings, as they struggle to interpret spoken cues (Shin, Smith and Gaines, 2015). This study builds on earlier research that used autistic hyposensitivity and hypersensitivity as the foundation for design inclusion (Seyedi, 2019). The design's visual component emphasizes color a lot, with brighter colors being more distracting to hypersensitive individuals than muted colors, and the reverse is true for hyposensitive individuals (Gaines et al., 2016). The basic mechanism of categorizing colors perpetually remains consistent between individuals with ASD and those without. However, the heightened sensitivity to sensory stimuli that is typical of ASD may affect color perception, with individuals having this condition leading to a dislike of certain colors that are generally preferred by neurotypical individuals. 85 percent of children with ASD perceive colors with greater intensity than usual children and are aroused by environments rich in color (Paron-Wildes, 2005).

Variations in materials and surfaces can significantly affect the way autistic children perceive touch, leading to alleviation or stimulation. Soft organic textures are more calming and delightful to them. The tactile sensory experience aids in social and emotional development (Shin, Smith and Gaines, 2015). To meet the needs of autistic individuals, multisensory textiles offer important features that enable them to enjoy tactile interactions and alleviate behavioral disorders such as anxiety (Ahlquist, 2015). Textile artist Ellie Turner creates intricate textures that depict the visual connections and sensory experiences of autistic children with various materials and objects. Children with autism are highly sensitive about their clothing and overall appearance (Kyriacou, Forrester-Jones and Triantafyllopoulou, 2021). An autistic individual's choice of attire influences their moods and emotions. The fabric's tactile quality determines their enjoyment experience. Stress, anxiety, and disorientation are brought on by a bad experience with fabric texture. Therefore, adaptive features pertaining to modified body form, strength, and movement limitations, as well as psychological and social needs, would be taken into consideration during the design process to integrate functional clothing with sensory-based experiences. In case of tactile hyper-responsiveness, which the autistic child frequently experiences, the placement of texture in different areas of functional clothing will make it easy for them to access the material, and once the texture is deemed enjoyable, it can be used as a calming tactic (Smith and Sharp, 2012). As a coping strategy to lower stress and improve well-being, some individuals with autism choose appropriate clothing and repeatedly stroke or touch a specific texture of a fabric (Jones, Quingney and Huws, 2003). This also helps them to experience soothing sensory experiences (Ashburner et al., 2013).

Functional clothing and sensory implementation

Apparel is a fundamental necessity for humans, alongside sustenance and shelter. The body protection feature of clothing has been enhanced by its aesthetic qualities. Clothing can be a personalized and adaptable information platform in addition to its protective and aesthetic roles (Park and Jayaraman, 2001). Clothing significantly influences the daily lives of children with autism, just like it does for everyone else. It is a fundamental psychological and physiological necessity, as it provides comfort and safeguards against adverse external influences (Yellow Bus ABA, 2025). Clothing is even more important for children with autism since it allows them to be independent, safe, and comfortable while making dressing easier by reducing the challenging aspects of dressing, such as buttons, zippers, and closures. It is significantly influential in enhancing the quality of life for them (Kaur and Chhabra, 2024).

By definition, functional clothing is tailored to fit the needs of each user and engineered to meet performance standards under difficult conditions (Gupta, 2011). It may have technological features that can be applied in telemedicine, therapy, rehabilitation, communication, and other fields. Functional clothing assemblies are ergonomically designed to maximize comfort and performance for the wearer and minimize movement restriction. There are three essential qualities upon which the integration of electronic sensors into functional clothing relies. Firstly, it is worn rather than carried, thus becoming an extension of the user; secondly, it is controllable by the user, not always requiring conscious thought or effort; and finally, it functions in real time, remaining perpetually active while possessing a sleep mode, allowing for interaction with the user at any moment (Kumar and Vigneswaran, 2016). It also results in biosensing clothing, which, when worn adjacent to the skin, is utilized to monitor essential physiological characteristics such as heart rate, blood oxygen levels, pulse rate, and core body temperature. It can additionally facilitate a behaviorally regulated experience for children with ASD by addressing their individual skills and interests through the development of tactile interfaces, thereby creating a visually and physically appealing environment (ibid.).

Research has well established the incidence of sensory processing challenges in children with ASD. One of the main ways to assist them is through adaptive functional clothing that is made to help with sensory sensitivities. Various research and studies in this field underscore the necessity of applying therapeutic and practical elements to clothing designs to enhance participation, comfort, and overall well-being. Kaur and Chhabra (2024) examined the development of functional clothing for autistic children, highlighting the challenges that sensory sensitivities present in everyday life. Their work emphasizes the necessity of specialized clothing that not only helps in tactile defensiveness but also prioritizes comfort, safety, and ease of wear. The research focused upon functional clothing ought to alleviate sensory discomfort while fostering independence in dressing, a common challenge for the children on the spectrum. Their systematic review indicated that sensory-based techniques, including wearable interventions, have demonstrated potential in modulating sensory responses. However, additional empirical evidence is required to validate the long-term efficacy of sensory functional clothing as a therapeutic intervention, as the results of the studies are not always the same. Further, sensory clothing can positively affect engagement in daily activities, improve self-regulation, and reduce stress levels (Lawson et al., 2022). Through temporal analysis the research reinforces the argument to include sensory garments as assistive tools that extend beyond mere comfort to promote enhanced participation in social and educational settings. Khalid (2021) made a contribution by focusing on the design development of adaptive and sensory-friendly clothing for autistic children. Her work emphasizes practical design solutions like tagless labels, adjustable fasteners, seamless construction, and breathable fabric. Khalid’s research indicates that clothes should strike a balance between therapeutic benefits and aesthetic value, enabling children with ASD to wear clothes that alleviate discomfort while preserving their sense of style and social identity.

Functional clothing development directly addresses sensory and tactile issues, though there is a deficiency in evidence concerning its long-term effects (Khalid, 2021). Quantifiable advantages are demonstrated in participation through experimental studies, while design-oriented research offers pragmatic methodology for garment development. These collectively advocate for an interdisciplinary methodology that integrates design, sensory understanding, and occupational therapy to enhance clothing options for children with autism. Based on the literature review and the need for further research, the objectives of the study were framed as follows:

- To examine the efficacy of sensory processing interventions, encompassing clothing-based approaches, in the management of sensory sensitivities in autistic children.
- To evaluate the impact of sensory-based adaptive functional clothing on the engagement and daily functioning of children with Autism Spectrum Disorder (ASD).
- To explore adaptive and sensory-based apparel design that harmonizes comfort, aesthetics, and practicality for children with ASD.

Methodology

The research is an exploratory study that aided in getting insights into the sensory experience of clothing on autistic children, ultimately leading to an acceptable experimental approach to design development and sensory integration. A pretest-posttest repeated measures design was used for two weeks to examine if the sensory garment led to behavioral change in autistic children when in distress. Informed consents were provided by the parents and caregivers to undertake the study in the presence of clinical psychologists. Purposive sampling was followed to select 30 autistic children of age group 6-14 years from the Autistic Society of West Bengal. Each selected autistic child exhibited at least one sensory pattern that was either significantly different from typical patterns or less pronounced than those of their peers.

To gain a more comprehensive understanding of the psychological and behavioral indicators in children with Autism Spectrum Disorder (ASD) and to identify the appropriate design requirements, interviews were conducted in the presence of special educators and caregivers. Data was collected through a questionnaire based on a sensory assessment, and the chi-square test was employed to test the significance of the data. For sensory assessment, engagement and impact in four categories were highlighted as Category 1: Tactility on Daily Objects, Category 2: Tactility in Clothing, Category 3: Visual Sensation, and Category 4: Auditory Sensation. The chi-square test results, based on the observed and expected data values, are presented in Table 1 as $X^2a=1.23$, $X^2b=0.97$, $X^2c=2.35$, and $X^2d=0.17$.

Table 1: Data set based on sensory assessment for autistic children

Category A: Tactility on daily objects

	Agree		Neutral		Disagree		
	O	E	O	E	O	E	
Individual	17	15.55	10	8.34	28	31.10	**55**
Tally	24	25.44	12	13.65	54	50.89	**90**
	41		**22**		**82**		**145**
		(O-E)^2/E					**Chi-Square**
		0.12		0.28		0.34	**1.23**
		0.09		0.23		0.18	

Category B: Tactility in clothing

	Agree		Neutral		Disagree		
	O	E	O	E	O	E	
Individual	27	29.43	9	8.45	10	8.12	**46**
Tally	60	57.57	16	16.54	14	15.88	**90**
	87		**25**		**24**		**136**
		(O-E)^2/E					**Chi-Square**
		0.22		0.03		0.35	**0.97**
		0.10		0.02		0.25	

Category C: Visual sensation

	Agree		Neutral		Disagree		
	O	E	O	E	O	E	
Individual	18	18.22	6	5.33	24	24.44	**48**
Tally	23	22.77	6	6.66	31	30.55	**60**
	41		**12**		**55**		**108**
		(O-E)^2/E					**Chi-Square**
		0.00		0.07		0.01	**0.17**
		0.00		0.07		0.01	

Category D: Auditory sensation

	Agree		Neutral		Disagree		
	O	E	O	E	O	E	
Individual	28	32.13	13	9.66	27	26.2	**68**
Tally	75	70.87	18	21.33	57	57.79	**150**
	103		**31**		**84**		**218**
		(O-E)^2/E					**Chi-Square**
		0.61		0.86		0.02	**2.35**
		0.23		0.62		0.01	

At significance level 0.05, the chi-square values for all four categories are < 5.99, showing that individual and tally are not statistically different with respect to the responses within the categories A, B, C, and D. Further, an ANOVA test was conducted for the four categories for both individual (Table 3) and tally responses (Table 4) based on the data set in Table 2. The results reveal that the p-values of the categories are much greater than the level of significance of 0.05, thus concluding that the categories are not significantly different under the responses in both the individual and tally cases. This assists in examining one or two categories extensively in the posttest survey.

Table 2: Data set on 4 categories of sensory assessment under individual and tally responses

Individual responses				
	A	**B**	**C**	**D**
Agree	17	27	28	18
Neutral	10	9	13	6
Disagree	28	10	27	24
Tally responses				
	A	**B**	**C**	**D**
Agree	24	60	75	23
Neutral	12	16	18	6
Disagree	54	14	57	31

Table 3: ANOVA for the four categories under individual responses

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Responses	442.17	2	221.08	5.62	0.042085	5.14325285
Categories	98.92	3	32.97	0.83	0.520142	4.75706266
Error	235.83	6	39.30			
Total	776.92	11				

Table 4: ANOVA for the four categories under tally responses

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Responses	2366	2	1183	3.65	0.0919	5.143253
Categories	1425	3	475	1.46	0.3154	4.757063
Error	1946	6	324.33			
Total	5737	11				

The research addresses a significant challenge in the design and development of sensory-based textile prototypes: the integration of conventional hardware components with textiles. Based on earlier research, three ways to attach off-the-shelf electrical devices to fabrics were provided. The first method involves fabricating fabric PCBs, or iron-on circuits, to directly attach electronics to a textile substrate; the second method involves incorporating electronic sequins to create wearable displays and other artifacts; and the third method involves implementing socket buttons to facilitate the connection of pluggable devices to textiles.

Textile structures can be categorized into woven, non-woven, and knitted fabrics. The motivation to integrate sensory mechanisms into knitted fabric arises from their use as stretchable material in the fabrication of laminated garments and also the level of comfort it can provide to the wearer. The fabric of choice for developing the garment as a foundation is knitted fleece. The kimono-styled (Figure 1) t-shirt, which features a detachable embellished kangaroo pocket, is designed as a pattern for children with autism. The t-shirt features a shoulder opening with a magnetic button closure for convenient wear. Adornment with LEDs and other components is sewn onto the kangaroo pocket as a surface embellishment in the form of an abstract tree design (Figure 2). This type of sequin is functional, durable, and significant in its capacity to imply a diverse range of designs.

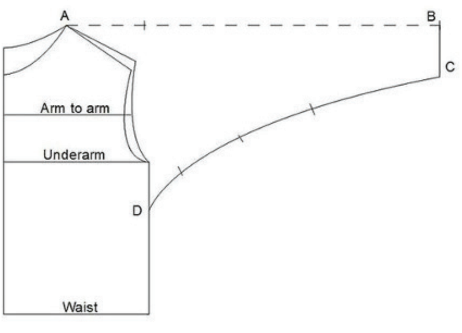


Figure 1: Kimono sleeve pattern

Figure 2: Surface embroidery using thread and LED sequins

The system design for the sensory mechanism (Figure 3) includes implementation steps as follows:

- Designing the input device: Choosing the appropriate touch sensor and integrating it with the microcontroller. The ATmega328P is the basis for the Arduino UNO microcontroller board. It has 14 digital input/output pins (6 of which can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB port, a power jack, an ICSP header, and a reset button (Arduino, n.d.). It contains all necessary components to facilitate the microcontroller.

- Setting up the transceiver: Configure using the Wi-Fi module (ESP-8266 Node MCU 1.0) for communication. The ESP8266 Node MCU 1.0 module is a system on chip (SOC) microcontroller primarily utilized for the development of endpoint Internet of Things (IOT) applications. It is referred to as an independent wireless transceiver, available at a very economical price. It facilitates internet connectivity to various applications within embedded systems (Elprocus, n.d.).
- Designing the output device: Integrating the chosen output device (LED) with the receiver's microcontroller. Figure 4 denotes the block diagram for the sensory mechanism.

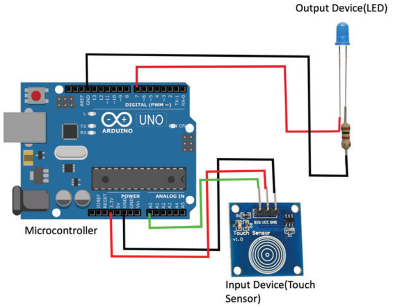


Figure 3: System design for the sensory mechanism

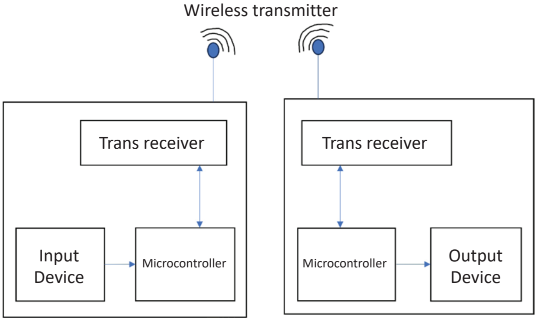


Figure 4: Block diagram for the sensory mechanism

Based on secondary research, interpretative phenomenological analysis was used to investigate design features that can be included in functional apparel to improve sensory experience. Interpretative phenomenological analysis was chosen over other qualitative methodologies since it focuses on the expressed experiences of individuals with specific social phenomena, in this case the tactile and visual sensations of autistic children through functional clothing.

Results and Discussion

The current research explores the possibility of combining interaction design with functional clothing, a relatively new and exciting segment of the technical textile group that can be defined as a generic term including all types of clothing or assemblies that are specifically engineered to deliver a predefined performance or functionality to the user, in addition to its normal function (Pargai, Gahlot and Rani, 2015). It is ergonomically designed to have a minimal inhibiting influence on mobility while providing the autistic children with optimal comfort and performance.

The sensing mechanism is integrated into the functional garment, designed for prolonged close contact with the body. According to Chakrabarty (2019), sensory integration is a therapeutic strategy employed by practitioners to stimulate the child's neurological system, consequently facilitating the development of motor abilities, speech patterns, and appropriate socialization. An individual needs the following mechanism to self-regulate in relation to the environment:

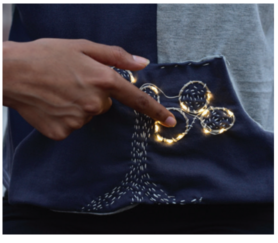
- Modulation: The brain activates or deactivates neural switches to regulate its function and, consequently, an individual's activity level. The regulatory process is contingent upon the specific task or activity being performed.
- Inhibition: The brain diminishes the linkage between sensory input and behavioral response when specific sensory information is unnecessary for executing a certain activity.
- Habituation: The process by which an individual becomes acclimated to familiar sensory stimuli, resulting in the brain's automatic disregard of such inputs.
- Facilitation: The brain fosters connections between sensory input and behavioral output by transmitting signals of discomfort or satisfaction. Facilitation indicates when to cease activities or provides the cue to proceed with enjoyable pursuits.

The sensory mechanism embedded into the detachable kangaroo pocket of the kimono t-shirt considers variables linked to human-machine interaction, including comfort, mobility, usability, and aesthetics, and was meant for the purpose of modulation. It has augmented function and emphasizes the incorporation of technology with conventional garments, rendering the technology an integral component of the apparel. The Arduino touch sensor is one of the most basic forms of input devices that is both durable and straightforward to operate, requiring minimal physical effort. Thus, it is incorporated into the system design. The Arduino UNO microcontroller serves as the transceiver. It is equipped with a 16 MHz ceramic resonator, a USB (Universal Serial Bus) connection, a power port, an ICSP (In-Circuit Serial Programming) header, a reset button, and 14 digital input/output pins, six of which can be utilized as PWM (Pulse Width Modulation) outputs. The output device is in the form of an LED (light-emitting diode), which is very cost-effective and simple to implement. It provides an immediate visual display in the form of light and was a facilitator in the design. The user interface is nuanced and depends on sensor input from both the user and the environment to automate tasks. It is engineered to be inconspicuous and to minimize the deliberate demands on users through the automation of functions.

People learn to adjust to their surroundings by using all of their senses, such as smell, sight, taste, sound, and touch. Sensory integration is the ability to put together information from different senses. It is essential for making sense of a situation and deciding what to do. Autistic children are more likely to have problems with touch than with other senses. Many kids with Autistic Spectrum Disorder are very afraid of being touched. These symptoms could be because of the clothes they wear or the tags and labels on them. When autistic kids are around things that make them feel bad, they feel emotional pain and worry. On the other hand, tactile modality is most often seen to provide people positive feelings when they think they can control it better.

As part of qualitative research, phenomenology, hermeneutics, and idiography are three philosophical approaches to interpretative phenomenological analysis. Phenomenology is a way to comprehend how people feel about things that are happening to them (Smith, Larkin and Flowers, 2009). The garment developed aroused immense curiosity among the autistic children, and they found it to be a playful product. Hermeneutics refers to the dynamic connection between the researchers' understanding of the participants' experiences and their own personal view of the results. The garment created interactivity for the autistic children, and like any other visual aid used for teaching schedules to perform daily activities independently, they found it to be one form of play. Idiography refers to the researcher's commitment to gather in-depth data in order to see things from the participant's perspective. The interactive experience of the autistic children paved a pathway to understanding that a garment can be a mode of playfulness, helping in creating a positive environment for the autistic child and reducing distress situations to a major extent. Autism Spectrum Disorder is a complex neurological disease that is difficult to comprehend completely. Every autistic child has unique and different needs that differ from other kids. Wearing clothes that are attractive, feel good, and are comfortable can greatly enhance the quality of life for these groups. The functional clothing design has the potential to provide tactile and visual sensory features for autistic individuals by including emotive consideration, which could promote social inclusion and improved adaptation for autistic children. Table 5 provides details about the prototype development aimed at fulfilling both functional requirements and sensory needs through touch and vision.

Table 5: Prototype development for tactile and visual sensory experience

S.No.	Functional clothing	Sensory implementation	Design description	Purpose
1.		Touch sensor as input device and light (LED) as output device	The tactile embroidery is created in the form of a geometric tree. Running stitch is used.	The natural motif of the embroidery helps the autistic children to relate to elements in the environment, enabling them to adapt in the social setup.
2.		The touch sensor and the LED are embedded in the detachable kangaroo pocket.	The double-layered detachable kangaroo pocket has a built-in circuit.	Constant stroking of the surface gives them playful experience within the garment.
3.		The output device (LED) is embroidered around the tree motif.	The kimono, which is two-colored and paneled, features a detachable kangaroo pocket. The detachable pocket has embroidery details for design interaction.	The embroidery with touch sensitivity will enable autistic children to experience tactile interaction and reduce behavioral issues like anxiety.
4.			The kimono has a magnetic closure at the shoulder, enabling hassle-free wearability, and the material used is cotton fleece.	The softer surface of the kimono helps in evoking stimulation in autistic children and helps them to feel calm and safe.

Prototype testing

Using the pretest-posttest repeated measures design as shown in Figure 5, three comparisons were made, that is, baseline: whether the outcome changes over the first week's wait period without any intervention; intervention: whether the intervention is effective; and post-test: whether there are overall changes from the first to the last meeting. 32 children having Autism Spectrum Disorder within the age group of 6-14 years were selected to carry out the testing. One parent dropped out after the baseline period without providing any reason, and one child refused to wear the garment, saying that he did not like the design. The final sample included 30 autistic children who participated in the testing process.

The study explored the effect of sensory-based functional clothing on the behavioral containment of autistic children. The various findings suggested that the children or their caregivers selecting sensory garment may improve adaptation to sudden surges of stimuli containing behaviors like anxiety, aggression, etc. This is consistent with the evidence showing significant and meaningful improvements in autistic children's attitudes and behaviors. The paired t-test shows a p-value $\approx 6.46 \times 10^{-14}$ which is far below 0.05, showing significant improvement in satisfaction level after using the sensory-based adaptive functional clothing.

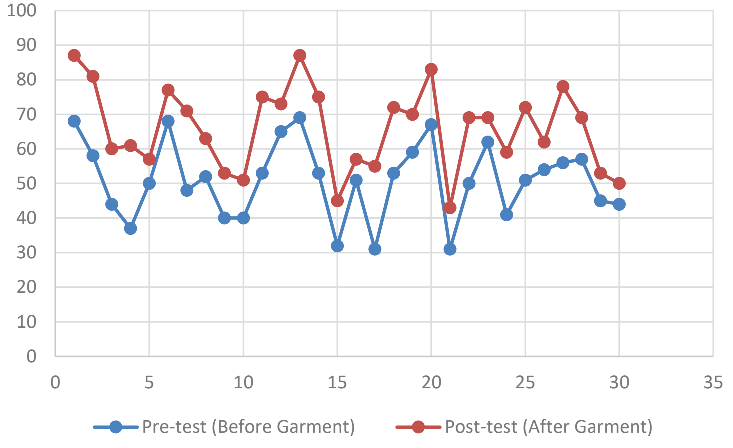


Figure 5: Graph showing satisfaction level during testing of prototype

Conclusion

Children with autism have a lifelong condition that impacts their capacity to communicate, interact with others, and control their behaviors. Due to their heightened physical sensitivity compared to typical individuals, children with autism often feel overwhelmed by their surroundings, primarily because of sensory processing issues. This can make it challenging for them to understand and adapt to their environment, leading to increased anxiety. In the present research, integration of functional clothing with sensory design has been shown through a design direction by incorporating touch-sensitive surface ornamentation in the form of embroidery where an output device in the form of light (LED) is embedded in the tree motif, inspired by nature, and is operated by a touch sensor input device. The textured surface placements in the form of design detailing on the garments give the autistic child easy access to tactile and visual sensory experiences, enabling them to cope and adapt to change efficiently. The goal of this research was to produce a corpus of meaningful work that could be interacted with in order to provide children with autism spectrum disorders with good and engaging experiences. The research highlighted limited design considerations given to autistic children and awakened the nascent need for sensory-based functional clothing, thereby aiding autistic children and building a platform for design addressing disability.

References

Ahlquist, S., 2015. Textile environments and tactile interfaces: responsive multi-sensory architectures for children with autism spectrum disorder. *AIA Academy of Architecture for Health Journal*, 18, pp.4–15. [online] Available at: <https://www.researchgate.net/publication/290195016_Textile_Environments_and_Tactile_Interfaces_Responsive_Multi-Sensory_Architectures_for_Children_with_Autism_Spectrum_Disorder> [Accessed 29 September 2024].

Arduino, (n.d.). *Arduino UNO R3*. [online] Available at: <https://docs.arduino.cc/hardware/uno-rev3/> [Accessed 12 June 2025].

Ashburner, J., Bennett, L., Rodger, S. and Ziviani, J., 2013. Understanding the sensory experieneces of young people with Autism Spectrum Disorder: a preliminary investigation. *Australian Occupational Therapy,* 60(3), pp.171-180.

Autism Speaks, (n.d.). *Pervasive developmental disorder – not otherwise specified (PDD-NOS)*. [online] Available at: <https://www.autismspeaks.org/pervasive-developmental-disorder-pdd-nos> [Accessed 1 September 2025].

Cañete, R. and Peralta, M.E., 2022. ASDesign: A user-centered method for the design of assistive technology that helps children with autism spectrum disorders be more independent in their daily routines. *Sustainability*, [e-journal] pp.1-27. https://doi.org/10.3390/su14010516.

Case-Smith, J., Weaver, L.L and Fristad, M.A., 2015. A systematic review of sensory processing interventions for children with autism spectrum disorders. *Autism,* [e-journa] 9(2), pp. 133-148. https://doi.org/10.1177/136236131351776.

Chakrabarty, N., 2019. *Development of sensory assessment battery for children with autism spectrum disorder.* Ph.D. Ramakrishna Mission Vivekananda Educational and Research Institute Coimbatore.

Douglas, S.N., Shi, Y., Das, S. and Biswas, S., 2022. Validation of wearable sensor technology to measure social proximity of young children with autism sprectrum disorder. *Focus on Autism and other Developmental Disabilities, Sage Publication*, [e-journal] 37(1), pp.24-33. https://doi.org/10.1177/10883576211028223.

Elprocus, (n.d.). *ESP8266 Wi-Fi module: pin configuration & its applications.* [online] Available at: <https://www.elprocus.com/esp8266-wi-fi-module/> [Accessed 12 June 2025].

Gaines, K., Bourne, A., Pearson, M. and Kleibrink, M., 2016. *Designing for autism spectrum disorder.* New York: Routledge.

Ghazali, R., Sakip, S.R.M. and Samsuddin, I.S., 2018. The effects of sensory design on autistic children. *Asian Journal of Behavioural Studies,* pp.68-83.

Grandgeorge, M. and Masataka, N., 2016. Atypical colour preference in children with autism spectrum disorder. *Frontiers in Psychology,* [e-journal] 7. https://doi.org/10.3389/fpsyg.2016.01976.

Gupta, D., 2011. Functional clothing- defination and classification. *Indian Journal of Fibre & Textile Research,* 36(4) pp.321-326. [Online] Available at: <https://www.researchgate.net/publication/296845630> [Accessed 29 September 2024].

Indian Rett Syndrome Foundation, (n.d.). *Rett syndrome*. [online] Available at: <https://rettsyndrome.in/> [Accessed 12 April 2023].

Jones, R.S.P., Quigney, C. and Huws, J.C., 2003. First-hand accounts of the sensory perceptual experiences in autism: a qualitative analysis. *Journal of Intellectual & Developmental Disability,* [e-journal] 28(2), pp.112-121. https://doi.org/10.1080/1366825031000147058.

Kaur, H. and Chhabra, J., 2024. Development of functional clothing for sensory sensitivities of children with autism spectrum disorder. *Journal of the Textile Association,* 84(4), pp.1-12.

Khalid, I., 2021. *Adaptive and sensory friendly clothing for children with ASD,* Bachelor of Industrial Design . Toronto: Humber instutute of Technology and Advanced learning.

Kommu, J.V.S., 2011. Research on autism spectrum disorder in India. *National Institute of Mental Health and Neurological Sciences,* [online] Available at < https://www.researchgate.net/publication/261474536_Research_on_autism_spectrum_disorders_in_India> [Accessed 1 September 2025].

Kumar, L. and Vigneswaran, C., 2016. *Wearable electronics*. In: Electronics in Textiles and Clothing: Design Product and Application. New York: CRC Press Taylor and Francis Group, pp. 1-67.

Kyriacou, C., Forrester-Jones, R. and Triantafyllopoulou, P., 2021. Clothes, sensory experiences and autism: is wearing the right fabric important?. *Journal of Autism and Development Disorder,* [e-journal] 53(4), pp.1495-1508. https://doi.org/10.1007/s10803-021-05140-3.

Lawson, L.M., Foster, L., Hamner, K. And Wright, L., 2022. Exploring effects of sensory garments on participation of children on the autism spectrum: a pretest-posttest repeated measure design. *Occupational Therapy International,* [e-journal] 1, pp. 1-8. https://doi.org/10.1155/2022/3540271.

Mikami, K. and Matsumoto, H., 2007. Differentiation between childhood autism and Asperger's syndrome. *Japanese journal for Cliinical medicine,* 65(3), pp.487-491.

Pargai, D., Gahlot, M. and Rani, A., 2015. Designing and construction of functional clothing for a child with disability: A step towards the social responsibility. *The International Journal of Social Sciences and humanities Invention,* 2(9), pp. 1534-1541.

Park, S. and Jayaraman, S., 2001. *Textile and computing: background and opportunities for convergence.* Presented at: Proceedings of the 5th IEEE International Symposium on Wearable Computers, Atlanta, Georgia, USA, 16–17 November 2001. New York: ACM.

Paron-Wildes, A., 2005. Sensory stimulation and autistic children. *Implications,* 06(04), pp. 1-5. (Search)

Perrin, J.M. and Coury, D.L., 2012. Improving health care for children and youth with autism and other neurodevelopmental disorders. *Pediatrics,* [e-journal] 130(2).

Seyedi, F.D., 2019. *Due to the enhancement of textiles,how can we cater sensory textles for autistic audiences in a secondary education setting?.* [Online] Available at: <https://www.researchgate.net/publication/332567307> [Accessed 29 September 2024].

Smith, J.A., Larkin, M. and Flowers, P., 2009. *interpretative phenomenological analysis: theory, method and research.* London: Routledge, Taylor and Francis Group.

Smith, R.S. and Sharp, J., 2012. Fascination and isolation: A grounded theory exploration of unusual sensory experiences in adult with asperger syndrome. *Journal of Autism and Developmental Disorders,* [e-journal] 43(4), pp. 891-910. https://doi.org/10.1007/s10803-012-1633-6.

Shin, S-J.H., Smith, B. and Gaines, K., 2015. *Investigation of therapy clothing products for children with autism spectrum disorder.* s.l., International Textile and Apparel Association.

South, M. and Rodgers, J., 2017. Sensory, emotional and cognitive contribution to anxiety in autism spectrum disorder. *Sec. Brain Health and Clinical Neuroscience, 11.* [Online] Available at: <https://www.frontiersin.org/journals/human-neuroscience/articles/10.3389/fnhum.2017.00020/full>[Accessed 29 September 2024].

Sruthi, M. (n.d.). What are the 5 different types of autism? *MedicineNet*. [online] Available at: <https://www.medicinenet.com/what_are_the_5_different_types_of_autism/article.htm> [Accessed 13 October 2025].

Tseng, M-H., Fu, C-P., Cermak, S.A., Lu, L. and Shieh, J-Y., 2011. Emotional and behavioral problems in preschool children with autism: relationship with sensory processing dysfunction. *Research in Autism Spectrum Disorders,* 5(4), pp. 1441-1450.

Verma, J.K. and Mohapatra, S., 2016. Childhood disintegrative disorder as a complication of chicken pox. *Indian Journal for Psychological Medicine*, 38(1), pp.65-66.

Willis, C., 2006. *Teaching young children with autism spectrum disorder.* s.l.: A Griffin House Book.

World Health Organization, 2023. *Autism spectrum disorders*.[Online] Available at: <https://www.who.int/news-room/fact-sheets/detail/autism-spectrum-disorders> [Accessed 1 September 2025].

Wright, S. and Wright, B., 2005. What is autism?. *Autism speaks*. [Online] Available at: <https://www.autismspeaks.org/what-autism> [Accessed 4 September 2025].

Yates, M.K, 2016. *Building better schools:a new model for autism inclusion in seattle,* s.l.: University of Washington.

Yellow Bus ABA, 2025. *Clothes for children with autism*. [online] Available at: <https://www.yellowbusaba.com/post/clothes-for-children-with-autism> [Accessed 29 August 2025].

About the authors

Tulika Saikia is Assistant Professor and former Course Coordinator of the Department of Fashion and Lifestyle Accessories of NIFT, Kolkata. With a BDes in Knitwear Design from NIFT Kolkata and an MDes from NIFT Delhi, she is currently pursuing her PhD from her alma mater. Her association with export and buying houses has helped her develop expertise in the field of design thinking and creative problem solving, gaining field experience with brands like Mothercare, Zara, Vero Moda, and Only. Her forte also lies in graphic design and typography design. Tulika has worked for Cognizant Technology Solutions Pvt. Ltd. in the Cognizant Interactive Team. She also has academic experience with NID as visiting faculty and Lovely Professional University, where she headed the School of Fashion Design. She has publications in the field of inclusive design, craft, sustainable design, and functional and adaptive clothing, including paper presentations at national and international conferences.

tulika.saikia@nift.ac.in

Sandip Mukherjee is Professor in the Department of Fashion Design at NIFT Kolkata. He specializes in the area of woven and knitted textiles, technical textiles, functional clothing, and smart garments. A postgraduate in textile technology from the University of Calcutta and a PhD from Maharshi Dayanand University, he has 30 years of experience, including 21 years in academics and 9 years in the textile industry. His passion for academics and innovation in textiles, along with traditional Indian crafts, drove him to join NIFT in 2008. He has several publications in national and international journals, including paper presentations at international conferences. He contributed a chapter on ‘Weft Knitted Fabrics’ in the book ‘Textile & Clothing Design Technology’ published by Taylor & Francis Group. He got a patent in March 2024 for an electronically developed table loom. He is currently the Chairperson of the Fashion Design department and has held various positions in the NIFT Head Office and Kolkata.

sandip.mukherjee@nift.ac.in

Dalia Nandi is presently working as Assistant Professor in the Electronics and Communication Engineering Department of the Indian Institute of Information Technology Kalyani. She has a BSc in Electronics honors from the University of Calcutta, followed by a BTech, MTech, and PhD from the Institute of Radio Physics and Electronics, University of Calcutta. Dalia has more than 20 publications to her credit in different IEEE, Elsevier, Wiley, MDPI, and Taylor & Francis group journals and 30 conference proceedings and two Indian patents. She was selected as a senior member of IEEE in the year 2017. Acknowledged for her research, she has received project grants from different funding agencies like IDEAS-TIH, ISI Kolkata, WBDST, etc. She is also serving as a reviewer and associate editor of different journals. Her research interests include 5G communication, IoT, embedded systems, quantum communication, etc.

dalia@iiitkalyani.ac.in

Traditional Wisdom to Artificial Intelligence: Strategies for Sustainable Fashion and Textile Practices in India

Nandini Lal and Sudha Dhingra

Abstract

The United Nations' agenda for Sustainable Development Goals (SDGs) seeks to protect the planet and reduce environmental impact. In recent times, sustainable practices in fashion and textiles have attracted considerable global attention due to their huge contribution to the waste generation system. Indian fashion and textile systems are extensive due to the abundance of locally available resources, diverse decentralized textile productions, handloom textile artisan skills, established manufacturing infrastructure, and enormous opportunities stemming from their emerging domestic market and young professionals. This research aims to identify and analyze the principal strategies explored by Indian enterprises in the domain of sustainable fashion and textiles in order to advance in this sector. The study seeks to understand the possibilities for Indian fashion and textile organizations of different sizes and formats to adapt sustainability.

The study involved a comprehensive study of 80 Indian business establishments that are implementing sustainable fashion and textile practices successfully. The sample included design houses, NGOs, online retailers, small-scale entrepreneurs, and leading Indian conglomerates like the Raymond's Group, Tata Group, Reliance, Birla Group, etc. The research entailed a close examination of sustainable strategies employed by fashion and textile companies as well as the possibilities explored by them. The research findings suggest that Indian enterprises are employing various strategies, from traditional wisdom to artificial intelligence, to support sustainability. Traditional craft practices, eco-friendly materials and processing, and green entrepreneurship are the most popular strategies used in the Indian scenario. Craft-culture preservation, handloom, and ethical practices for social impact are other successful strategies employed by a considerable percentage of enterprises. Large enterprises are using AI-supported technologies for optimization and efficient actions at various stages, whereas small and micro enterprises are relying on green ethical practices and social impact. Energy efficiency, reduced carbon footprint, and circular economy have a small presence and require further action and training for real action. The study confirms the possibilities of new players to adapt to varied strategies in order to contribute to a sustainable future.

Keywords: Sustainable strategy, Indian fashion and textile organizations, traditional textile crafts, artificial intelligence for supply chain, sustainable material production

Introduction

The transition towards sustainable fashion is not just a temporary trend but a necessary step for the industry's future sustainability and progress. Niinimäki (2010) states that the focus is on the significance of eco-clothing in influencing consumer identity and ideology. The shift is supported by the research of Connolly and Prothero (2008), who argue that green consumption behaviors are gaining popularity as consumers become more aware of the environmental and social impacts of their purchasing decisions. Wahl (2016) explores sustainable solutions, emphasizing economic, social, institutional, and environmental interdependence within human society and the non-human environment. The industry's response to sustainability initiatives indicates a positive and encouraging direction. Arora (2023) highlights the increasing popularity of the sustainable apparel market in India, driven by rising consumer demand for eco-friendly fashion. It is essential to highlight that the ethical fashion market is experiencing significant growth worldwide, with predictions from industry experts indicating that this trend will persist in the coming years. "A New Textile Economy" by the Ellen MacArthur Foundation (2017) is in line with circular economy principles that focus on restoring and regenerating resources, ultimately benefiting companies, communities, and the ecosystem.

Recent research studies continue to shed light on the latest developments in sustainable fashion. A study conducted by Ciarli et al. (2021) covers the emerging trajectories and challenges of digital technologies for sustainable fashion. The study specifically explores the utilization of blockchain technology to enhance traceability and transparency in supply chains. A study by Tawiah et al. (2025) elaborates on the relationship between consumer behavior and sustainable fashion. They highlight the importance of raising consumer awareness and providing education to stimulate the demand for sustainable products. The studies highlight the complex challenges facing the fashion industry and emphasize the importance of ongoing research and innovation to address sustainability.

Furthermore, recent studies have surfaced, offering novel insights into sustainability within the fashion industry. A report published by Fashion Revolution (2023) emphasizes the increasing significance of transparency and traceability in the fashion supply chain. It urges brands to provide more details about their sourcing and manufacturing practices. The emphasis on transparency is widely recognized as essential for fostering consumer trust and encouraging ethical behavior throughout the industry.

The fashion supply chain can significantly benefit from the promising solutions provided by recent advancements in blockchain technology (Khanfar et al., 2021). Through thorough research and analysis, it is evident that blockchain technology has the potential to revolutionize the production process. By providing an unchangeable record of every stage, from sourcing raw materials to delivering the final product, blockchain ensures that all practices adhere to sustainability standards.

Many educators and research scholars are playing a crucial role in inspiring and guiding young designers to embrace sustainable practices. There is a growing recognition and appreciation for empathetic fashion, which indicates a change in design culture towards addressing social issues and enhancing the well-being of individuals (Armtrong and Niinimäki, 2014). Experts are exploring various concepts like zero-waste pattern cutting, natural dyeing and printing, hand stitching, recycling, upcycling, and handloom products as effective methods to enhance the sustainability of the fashion industry.

Academic settings are also delving into exploring the intersection between sustainability and technology. Universities and research institutions are actively incorporating sustainability into their curricula, fostering a culture of innovation among students to address the environmental challenges faced by the industry. A study conducted by Corbett, Dennehy and Carter (2023) sheds light on the significance of design education in driving sustainable practices. The study emphasizes the need to cultivate a new breed of designers who prioritize environmental and social responsibility.

The growing global sustainable market and India's emerging domestic and export market

Recent global market reports indicate that the ethical and sustainable fashion sector is undergoing significant expansion, driven by increased consumer awareness and policy shifts in favor of environmental responsibility. In 2023, the global ethical fashion market was valued at USD 9.81 billion and is anticipated to attain around USD 19.85 billion by 2030, exhibiting a compound annual growth rate (CAGR) of 10.2 percent (Statista, 2024; Business Research Company, 2024). This growth is propelled by increased customer demand for sustainable, ethically manufactured clothing, more stringent environmental restrictions, and advancements in circular fashion methodologies. In India, the domestic clothing market was valued at USD 115.7 billion in 2024 and is anticipated to reach USD 171.6 billion by 2034, exhibiting a CAGR of almost 4 percent (Nandi, 2025). This ranks India among the foremost global fashion markets, with the potential to surpass the UK and Germany in scale. India's textile and apparel export sector is strong, with projections indicating exports could exceed USD 65 billion by 2026, bolstered by worldwide demand for sustainable textiles and government programs like PM-MITRA parks and PLI schemes for textiles (Invest India, 2024).

India plays a pivotal role in sustainable raw material production, contributing around 23–25 percent of world cotton output (Cotton Corporation of India, 2024). India is the second-largest producer of silk and a significant manufacturer of synthetic and recycled fibers (Ministry of Textiles, 2025). Innovative ecological materials like hemp, organic cotton, kala cotton, and recycled polyester are increasingly being embraced by startups and prominent textile manufacturers.

The Indian fashion and textile industry

India's fashion and textile industry holds immense promise, thanks to its pool of talented young professionals. There are numerous individuals and groups dedicated to promoting sustainability in different ways. India's fashion industry is making great strides in adopting sustainable practices through various innovative approaches. 11.11 Ka-Sha, Doodlage, Raw Mango, Bodice, Rustic Hue, and others are active in designing and selling apparel made with fair and ethical methods, such as giving factory workers safe working conditions, collaborating with handloom weavers and artisans to produce handcrafted goods, sourcing recycled or organic raw materials, and upcycling waste from post-production and post-consumer sources. Gautam Gupta specializes in creating hand-spun fabrics using unique and unconventional materials such as bananas, bamboo, and coffee beans (Khandual and Pradhan, 2018). On the other hand, "Pero Recycle" and "Pero Upcycle" labels are dedicated to promoting environmental conservation (Nanda, 2019). According to Lal (2020), brands such as Akira Ming and Yarn Glory have a total inclination to manufacturing organic clothing.

The eco-friendly clothing market in India is experiencing steady growth, as manufacturers are actively implementing practices to reduce their environmental footprint (Lal and Rahman, 2013). Raymond Group and Reliance Industries have recently joined forces to introduce Ecovera, an eco-friendly fabric line. The Aditya Birla Group's Grasim has introduced Liva, a branded cellulose fiber. Sunil Sethi, the chairman of the Fashion Design Council of India, emphasizes India's rich heritage in sustainable practices, indicating that the country possessed inherent sustainability long before the rise of fast fashion disrupted traditional methods. He argues that, despite the perception that India is a latecomer to sustainability, the country has been implementing these practices long before the rise of fast fashion, as cited by Adhikary (2021).

A key model for India's sustainability drive is the integration of the handloom and craft sector into global fair-trade supply chains. This addresses the social, environmental, and economic pillars of sustainability, ensuring artisan livelihoods while promoting eco-friendly production. Organizations like SEWA, Okhai, Ethicus, and Antaran (Tata Trusts) are actively involved in connecting traditional handloom practices with modern ethical consumption trends (SEWA, n.d.; Okhai, n.d.; Ethicus, n.d.; Tata Trusts, n.d.). India's fashion-tech ecosystem is also evolving. Companies like Welspun (Indian Textile Journal, 2021) and ReshaMandi (Nainar, 2021) are using AI and blockchain for supply chain transparency. Virtual try-on technologies and AI-based demand forecasting reduce overproduction (Roy, 2024). Circular fashion models and upcycling initiatives by brands like Doodlage (Aggarwal, Singh and Krishna, 2024; Jain, 2020) and Paiwand Studio (Huggard and Choudhary, 2025) are promoting zero-waste strategies. India's young, digitally savvy consumers, combined with government policy support, are evolving sustainable fashion and textile possibilities and placing the country at the forefront of the global sustainable fashion movement.

This research was initiated to examine sustainable fashion and textile organizations in India and identify their key principal strategies for sustainability. The expected findings of this research will progress further for the creation of guidelines for sustainable fashion education.

Research Methodology

Research design

The study employed a qualitative research design, utilizing in-depth content analysis to systematically explore and interpret how fashion and textile organizations communicate their sustainability strategies and practices. The research focused on analyzing textual and visual content from the official websites, aiming to understand the representation of sustainability principles across different companies. The study incorporated approaches to identify patterns, codes, and themes within the data. The research framework is grounded in thematic analysis underpinned by sustainability. Websites of fashion brands served as the primary data source, offering an accessible platform to assess how sustainability is framed in various contexts, leading to a comprehensive framework that organizations use to present their sustainability efforts, thus imparting valuable insights for consumers and the fashion industry. The research emphasized the messaging strategies, visual content, and transparency of claims related to ethical production, environmental impact, and corporate social responsibility.

The researcher opted for a deductive approach in framing initial codes based on existing literature on sustainability while inductively identifying new themes that emerged from the data. This study utilized a single-method research choice focusing exclusively on qualitative content analysis to explore the representation of sustainability. The choice was made to ensure an in-depth examination of textual and visual content without being constrained by quantitative metrics.

Time horizon

The research followed a cross-sectional time horizon, with data collected in a single period from April to September 2024. This time-frame allowed the researcher to capture the state of sustainability communications as they appear on websites during that period, without considering changes over time.

Sampling strategy

The study used purposive sampling, targeting websites of fashion and textile organizations that explicitly claim to follow sustainable practices. The research context is global but focused on companies that have a strong online presence and are transparent about their sustainability efforts. This sample includes brands based in various geographical locations in India, serving diverse markets but with a common goal of promoting eco-friendly practices. The study aims to capture the broad spectrum of sustainability approaches, from niche eco-friendly startups to large-scale businesses.

The criteria for selecting websites included the following:

- The organization must publicly promote sustainability as a core value.

- It must offer product lines or services that aim to reduce environmental or social harm.
- Organizations of different sizes and formats (e.g., small-to-medium, large enterprises and large online retailers, and NGOs) were included to ensure diversity.

The researchers acknowledge that the content available on these websites is curated by the brands themselves, potentially resulting in bias towards self-promotion. Reflexivity in the analysis process ensures that the researchers remain aware of this limitation, avoiding assumptions based solely on the brand's portrayal of its practices. This is counteracted by cross-referencing claims with certifications and industry standards wherever available.

A total of 78 organizations were considered, encompassing a range of companies from MSMEs to large enterprises of fashion and textile, manufacturers, design houses, NGOs, and large multinationals, as mentioned in Table 1. This sample size is considered sufficient to capture the variety of sustainability strategies across different business formats and sizes.

Table 1: Frequency of business formats selected for the study

Business Format	
Social enterprise (NGOs)	13
Fashion business	26
Textile business	5
Retail supply chain platform	12
Luxury fashion brand	6
Traditional craft-based apparel business	15
Export house	1
Total	**78**

The business formats selected for the study include the following:

- Social enterprise (NGOs): Organizations focused on social impact, often supporting artisans and promoting ethical, sustainable practices. A "not-for-profit" organization prioritizes social, environmental, or cultural impact over profit, with revenue reinvested to further these mission-driven goals.

- Fashion business: Engages in the design, production, and sale of apparel and accessories.
- Textile business: Specializes in manufacturing and supplying fabrics and materials for the fashion industry.
- Retail supply chain platform: Connects producers, suppliers, and consumers to streamline the sale of fashion goods.
- Luxury fashion brand: High-end label known for exclusive, premium-quality apparel and unique design.
- Traditional craft-based apparel business: Integrates traditional craftsmanship into fashion, preserving cultural techniques and skills.
- Export house: Large-scale producer and exporter of fashion and textile products to international markets.

The categorization of business size (Table 2) in this study adheres to the definition established by the Ministry of Micro, Small and Medium Enterprises, Government of India (MSME Development Act, 2006), and is supported by recent industry research (Ministry of Micro, Small & Medium Enterprises, 2006). Micro enterprises with investments of not more than INR 1 crore and less than 10 employees specialize in specialist markets like bespoke tailoring or textile crafts, allowing for agility and personalized services. Small enterprises with investments not exceeding INR 10 crore and 10 to 49 employees and they may offer locally or online with limited distribution and low production capability. Medium enterprises with investments of not more than INR 50 crore and 50–249 employees, serving national or regional markets with greater manufacturing facilities, distribution, or brand visibility. Large enterprises surpass these thresholds, with 250 or more employees with large manufacturing facilities, global supply chains, and diverse product lines.

Table 2: Frequency of business size selected for the study

Business Size	
Large	14
Medium	3
Small	25
Micro	36
Total	**78**

Research phases

The research was conducted in the following phases:

Phase 1:

Data collection (April 24 to September 2024): Websites were systematically reviewed, and relevant textual and visual content was extracted.

Data extraction: Textual content was manually extracted from the selected sections of websites, including homepages, sustainability pages, product descriptions, corporate social responsibility reports, and featured stories.

Phase 2:

The extracted content was categorized into spreadsheets and coded for analysis. The coding process was systematic, involving thematic categorization to ensure the reliability of findings across various websites. Data management and coding processes ensure the robustness of the thematic analysis. As the study is based on publicly available website data, there are no direct ethical concerns related to participant confidentiality. However, the researchers remained mindful of the limitations associated with using self-reported content from organizations.

Phase 3:

A thematic content analysis was applied to the coded data to identify recurring patterns and differences in how organizations communicate their sustainability efforts. Data were categorized into specific themes related to sustainability, such as ethical labour, environmental responsibility, product innovation, etc. Table 3 illustrates this process.

Open coding was first applied to extract themes directly from the data. Initial codes are based on existing literature on sustainability in various online platforms of the fashion and textile industry. Initial codes were created to identify recurring terms such as “eco-friendly,” “organic materials,” “fair trade,” “environmental impact,” etc. Essential tactics such as “material sourcing,” “ethical production,” “circular fashion,” and “supply chain transparency” were recognized.

Axial coding was done to relate categories to one another. The codes were grouped into larger categories, such as artisan development, eco-friendly production, and transparency in supply chains. Finally, selective coding was used to consolidate themes that emerged as central to the brands’ sustainability narratives. Selective coding represented the principal theme of core sustainable practices, which included all techniques employed by sustainable fashion enterprises.

Table 3: Coding table

S.No.	Open coding	Axial coding	Selective coding
1.	"Transparent system from farm to finished garments" "AI combined with IoT ensures the quality and traceability" "Global Organic Textile Standard (GOTS)"	Traceability and certification	AI and technology for optimization
2.	"Circular business model" "100 percent zero leftovers" "Circular model of business"	Circular business models	Circular economy
3.	"Closed-loop production system" "Ethical production and wages"	Circular economy	Circular economy
4.	"Quality of life of craftsmen" "Local artisan training" "Supporting rural and local economies" "Cluster Development" "Supporting underprivileged women artisans" "Artisan upliftment for social Impact" "Decentralized craft production"	Artisan development	Decentralized system and artisan upliftment
5.	"Handloom weavers" "Handcrafted" "Handspun" "Upliftment of handloom" "Khadi handloom"	Handloom Handmade Khadi	Handloom and Khadi for sustainability
6.	"Revive old textiles" "Improved efficiency in craft space" "Heirloom and traditional weaves" "Preserving the craft"	Craft preservation Cultural heritage	Craft for cultural preservation
7.	"Natural dyes" "Handprint with natural dyes" "Eco-friendly dyes"	Eco-friendly material and processing Natural dyes Handprint	Eco-friendly material and processing
8.	"Focus on longevity and quality" "Social development" "Sustainable sourcing" "Green ethics reduce environmental impact" "Collaborate" "Product for a social cause" "Focus on inclusivity" "Eco-friendly garments and accessories" "Jewelry with recycling"	Sustainable business models Green entrepreneurship Sustainable products	Green entrepreneurship for sustainability

9.	"Minimize water usage during the textile manufacturing process" "Production as per sustainability standards" "Optimize material usage and minimize waste" "Transparent and ethical production" "Reducing unnecessary production"	Eco-friendly material and processing Sustainable production approach Ethical manufacturing	Sustainable production approach
10.	"Eco-friendly fibers and fabrics" "Organic cotton, hemp, and linen" "Kala cotton, indigenous cotton" "Eri silk, tasar silk, linen, wool" "Eco Tencel, Econyl" "Recycled polyester" "Natural products" "Sustainable farming" "Sustainable raw material"	Eco-friendly fiber Material innovation	Eco-friendly material and processing
11.	"Reducing the carbon footprint" "Monitor energy consumption: farm to retail" "Reducing unnecessary production" "Energy-efficient technologies in production" "Carbon negative" "Minimize water usage"	Energy-efficient carbon footprint reduction	Energy-efficient carbon footprint reduction
12.	"Livelihood for indigent women", "Work for social welfare" "Fair-trade and ethical wages" "Social development"	Fair wages Livelihood generation	Ethical practices for social impact
13.	"Recycle plastic waste" "Upcycle post-production fabrics" "Reduce fabric waste" "Zero waste methods" "Fabric scraps into new products" "Recycle plastic waste" "Yarn upcycling" "Reduce returns and waste"	Reduce Reuse Recycle Repurpose	Reduce - Reuse - Recycle - Repurpose
14.	"Long-lasting fashion and textiles" "Seasonless and slow fashion"	Slow and seasonless fashion and textiles	Slow and seasonless fashion

15.	"Storytelling to celebrate multi-layered cultures and ever-changing social conversations" "Conscious consumerism" "Educating individuals and organizations" "Promote handmade" "Encouraging customers to make informed choices" "Transparent information for customers" "Eco-conscious choices" "Creating awareness for pollution"	Conscious consumerism Customer education Creating awareness for sustainability	Consumer awareness
16.	"AI-powered" "AI optimizes logistics" "Optimizing material usage" "AI predicts customer demand accurately, reducing overproduction" "Virtual try-ons" "AI-driven systems to optimize inventory" "Prevent overstocking" "Predictive analytics" "AI-driven processes optimize water usage in production" "AI-based manufacturing processes" "Virtual product visualization"	AI for forecasting AI for inventory management AI for production optimization AI for customer demand AI for virtual visualization	AI and technology for optimization
17.	"AI supply chain optimization" "AI to manage organic cotton supplies" "Blockchain tracks, enhances transparency" "Blockchain ensures traceability" "Blockchain tracks from farm to retail"	AI for supply chain optimization Blockchain and transparency	AI and technology for optimization
18.	"AI for natural dye optimization"	AI for material usage	AI and technology for optimization
19.	"AI minimizes water usage" "AI to measure and report on water and energy usage"	AI for water and energy	AI and technology for optimization

Results and Discussion

The data analysis and interpretation, which aligned with the research objectives, utilized thematic analysis to examine the strategies employed by Indian fashion and textile organizations to achieve sustainability. The 13 themes identified illustrate the principal strategies employed by sustainable fashion and textile organizations in India (Figure 1).

Figure 1: Principal sustainable strategies
Source: Nandini Lal

Green entrepreneurship for sustainability

Green entrepreneurship is an overarching theme that encompasses all unique ideas for sustainable practices. It includes various approaches to reduce environmental impact, green ethics, self-employed women, sustainable sourcing, collaboration, products for a social cause, a focus on inclusivity, size inclusivity, eco-friendly outcomes with recycling, etc. For example, The Terra Tribe is a small green enterprise that promotes plant-based, PETA-approved clothing made from sustainable materials. The company fosters an environmentally conscious business model by focusing on vegan, eco-friendly materials and ethical practices. Suta is another example of an Indian fashion brand that engages in green entrepreneurship by integrating sustainability into every aspect of their business, from material sourcing to packaging.

Sustainable production approach

Natural dyeing processes are gaining popularity as a sustainable alternative to chemical dyes. Brands like Kriti Tula, Ashita Singhal, and Tilla use natural dyes sourced from plants, minerals, and insects. Larger manufacturers like Arvind Limited have successfully adopted eco-friendly methods of textile processing, such as waterless dyeing and recycled water systems. Sustainable practices are also seen in production approaches like zero-waste pattern-making, fabric scrap recycling, and upcycling to reduce waste. Designing strategies to reduce wastage, pollution, and energy consumption is a key component. The brand, Fabindia, follows a sustainable production approach by collaborating with artisans who use organic and natural fibers. Fabindia's production methods focus on minimizing environmental impact, ensuring that their entire process from raw material sourcing to finished products aligns with sustainable principles.

Energy-efficient carbon footprint reduction

Energy efficiency and carbon footprint reduction are crucial for reducing the environmental impact of the fashion and textile industry. Organizations achieve their goals by using energy-efficient technologies and renewable energy sources and optimizing manufacturing processes to reduce emissions. Textile manufacturer Welspun India has implemented AI for energy management in its factories, significantly reducing its carbon footprint. Welspun's energy-efficient practices and focus on low-impact dyes are geared toward minimizing the carbon emissions associated with textile production.

Decentralized system and artisan upliftment

India's decentralized textile craft system is integral to sustainable practices. Many Indian fashion brands, such as Raw Mango and Anokhi, collaborate with local artisans to preserve these traditional crafts while promoting sustainability. Decentralized systems bring production closer to rural and artisan communities, supporting local economies and reducing the environmental impact. The upliftment of artisans entails training and support to sustain their livelihoods. Brand Okhai empowers rural women artisans by providing training, fair wages, and a platform to sell their handcrafted products. This decentralized model supports artisan communities and enhances their quality of life by promoting sustainable employment.

Handloom and Khadi for sustainability

Handloom and Khadi production methods are inherently sustainable due to their low energy consumption, minimal environmental impact, and reliance on natural fibers. Khadi, which is hand-spun and handwoven, supports a sustainable and slow production process that uses no electricity. The Khadi Cult promotes khadi as a sustainable fabric that requires minimal resources for production.

Craft for cultural preservation

The use of traditional crafts not only promotes sustainability but also preserves cultural heritage. By valuing traditional crafts, companies can keep indigenous knowledge alive, support artisans, and connect consumers with cultural history through fashion and textiles. Qasab, Khamir, and many other NGOs work with the nomadic tribes of Gujarat to create handloom and embroidered products that reflect the region's cultural heritage. This initiative preserves heritage crafts and techniques while promoting sustainable fashion.

Circular economy

The concept of circularity is gaining traction in India, where companies focus on designing products that have longer life cycles and can be recycled, repaired, or repurposed. Circular fashion models discuss the afterlife; brands are creating take-back programs or repair services to prolong the life cycle. The circular economy in fashion promotes a "closed loop" with minimum energy leakage and harmful byproducts. Doodlage is a leading brand in circular fashion, specializing in upcycling industrial waste and post-consumer materials to create unique garments.

Eco-friendly material and processing

Indian textile companies are increasingly adopting sustainable materials. Organic cotton, grown without synthetic pesticides or fertilizers, has become particularly popular due to its lower environmental impact compared to conventional cotton. Brands like No Nasties and Ethicus emphasize the use of certified organic cotton and natural fibers in their collections. Eco-friendly materials, sustainable dyes, and environmentally friendly processing methods minimize pollution and environmental impact.

Ethical practices for social impact

Fair wages, livelihood generation, and ethical labor practices in safe conditions are a cornerstone of sustainability in the Indian textile industry. Fairtrade India is a prominent certification that ensures these practices; the ethical approach focuses on fair labor practices, fair wages, safe working conditions, and social welfare for workers. This approach promotes social equity and ethical treatment within the supply chain. SEWA (Self-Employed Women's Association) empowers rural women by providing fair-trade wages, safe working conditions, and training.

4 R's for waste reduction

The 4 R's approach minimizes waste by reducing it, reusing materials, repurposing discarded items, and recycling whenever possible. These 4 R's are part of indigenous traditional practices (Singh and Rani, 2021). The brand "I Was a Sari" repurposes old saris into new fashion items, turning waste into valuable products. 11.11/eleven (n.d.) focuses on creating garments with zero-waste patterns, while Upasana implements social initiatives that repurpose fabric waste into useful products. The 4 R's and waste reduction efforts also encompass the recycling of post-consumer textiles. Companies like Goonj collect old clothes and textiles, transforming them into products such as bags, mats, and garments for underserved communities.

Consumer awareness

Many Indian brands are focusing on consumer education to promote sustainable fashion choices. Tula and Satva, for instance, educate customers about the benefits of organic cotton and sustainable living through their marketing campaigns. Consumer awareness involves educating customers about sustainable practices and empowering them to make informed, eco-conscious choices. By raising awareness, companies encourage responsible consumption. The brand "No Nasties" uses transparent labeling and educational content to inform consumers about the environmental and social impacts of their choices. This approach promotes conscious consumerism and responsible purchasing.

AI and technology for optimization

Transparency and traceability are key aspects of sustainable supply chain management in India. Companies like Good Earth and Fabindia have implemented blockchain technology and IoT (Internet of Things) to ensure that their supply chains are transparent, enabling consumers to track the origin and production journey of the garments. Sustainable sourcing practices, including working with certified suppliers of organic or fair-trade fabrics, help ensure that the supply chain is ethically and environmentally responsible. AI and advanced technologies optimize production and inventory, reducing resource usage and minimizing waste. As collated in Table 4 and Figure 2, various Indian companies are using AI and technology to boost sustainability through optimization and waste reduction. AI aids in demand forecasting, minimizes overproduction, and enhances logistics. Technologies facilitate transparency and traceability, thereby ensuring responsibility and trust. Virtual visualization, prototyping, and try-ons are saving ample time and resources and making the process more efficient.

Table 4: The use of technology to boost sustainability

Technology	Company Name	Sustainability Impact
AI for demand forecasting (predictive analytics)	Raymond Ltd.	Reduced overproduction
AI for water/energy management	Arvind Ltd.	Minimized water and energy use
Blockchain for supply chain	ReshaMandi	Ethical sourcing and traceability
Virtual try-ons	Tata CliQ, Zivame	Reduced returns and lower carbon footprint
AI for waste reduction	Doodlage	Upcycling and fabric waste minimization
On-demand production	InkXE, Aks Clothing	Lower inventory and waste
AI for quality control	Welspun India	Reduction of defects and material saving
AI in sustainable farming	BOHECO	Eco-friendly raw material sourcing
Virtual sampling	ABFRL Ltd.	Less waste in sampling and prototyping
AI in circular fashion	Paiwand Studio	Textile waste, reuse and circular design

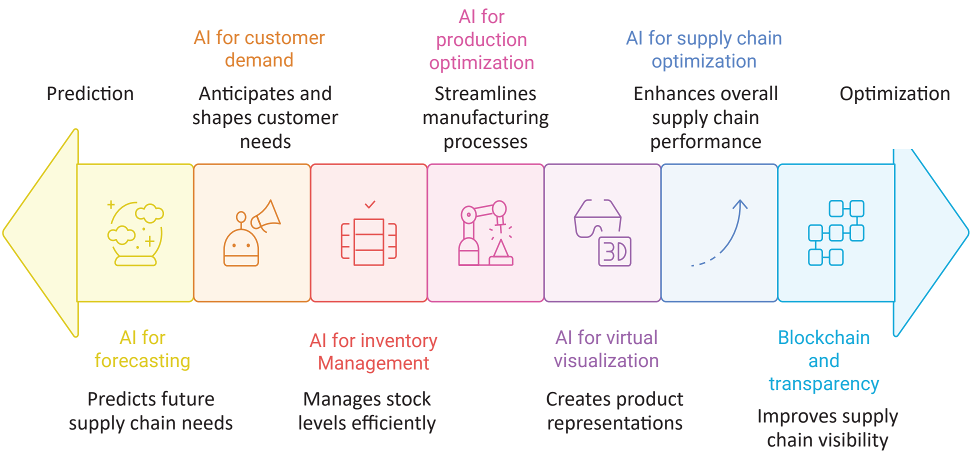


Figure 2: AI's role in supply chain, from prediction to optimization
Source: Nandini Lal

Slow and seasonless fashion

Slow and seasonless fashion counters the fast fashion model by focusing on quality, timeless design, and longevity. Slow fashion encourages consumers to buy fewer, high-quality items that last longer, reducing discarded clothing and promoting resource efficiency. Together, these approaches foster mindful consumption, encouraging consumers to keep items for extended periods. Brand 11.11/Eleven Eleven exemplifies slow and seasonless fashion by promoting emotional attachment to its garments and using traditional Indian textiles and craftsmanship. Designer brand Raw Mango also follows a seasonless model, creating collections that remain relevant year-round. By embracing these principles, brands contribute to a more sustainable fashion industry, emphasizing slow fashion and a lower environmental footprint. New brands for saris, like Suta and Taniera, are promoting timeless handloom products and believing in traditional wisdom.

Analysis

Many organizations are using multiple strategies to implement sustainability. Brands like Upasana and Tula are leading organizations using most of these strategies. Among large enterprises, "sustainable production approach" and "eco-friendly material and processing" are the most preferred strategies. Within small to medium organizations, where 80 percent were fashion brands, "craft for cultural preservation" is the most popular one. To determine the most popular strategy among different sizes and formats of business, frequency analysis methods were used.

Frequency analysis for preferred strategies in sustainability practices

To identify the most prevalent sustainability strategies adopted by Indian fashion and textile organizations, a frequency analysis was conducted on the data extracted from official websites. This analysis revealed that numerous sustainable fashion and textile organizations are implementing sustainable practices at various operational stages. Strategies with the highest frequency of occurrence were deemed the most favored ones, reflecting their widespread adoption across the industry. Figure 3 denotes the overall analysis, including all the sizes and formats of businesses, and shows that "eco-friendly materials and processes," "sustainable production approach," and "green entrepreneurship" are the three most preferred strategies.

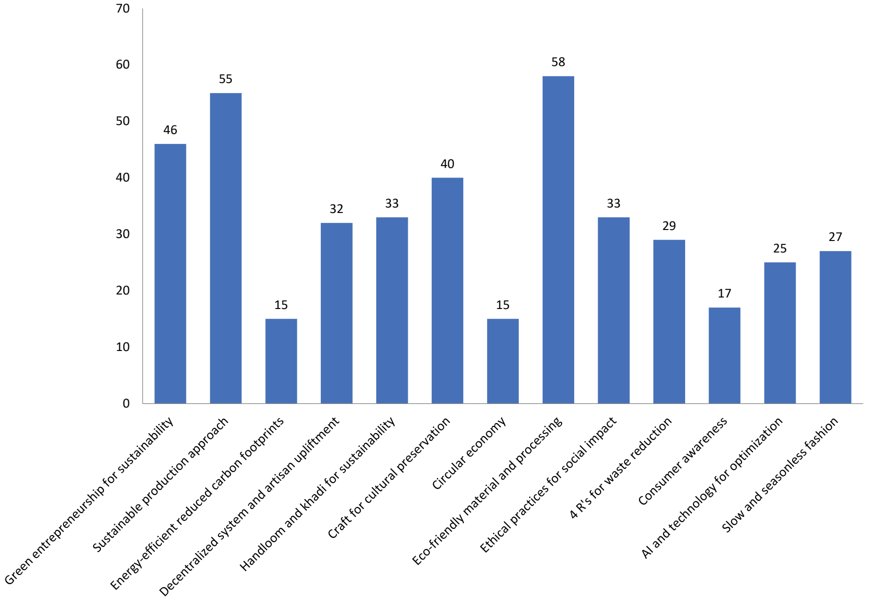


Figure 3: Frequency analysis for preferred sustainable strategies

Furthermore, a comparative frequency analysis of these strategies categorized by business size (Figure 4) and format (Figure 5) provides deeper insights to understand the potential of diverse sustainable strategies and their feasibility in the Indian context. It's important to understand how this strategy works with various businesses.

In large enterprises, the most favored strategy is "AI and technology for resource optimization," followed by "sustainable production approaches" and "eco-friendly materials and processes," which are also popular. In medium businesses, "sustainable production approach," "decentralized system for artisan upliftment," and "waste reduction through 4 R's are popular. Small-sized businesses utilize eco-friendly materials to promote sustainability. Many micro-enterprises are emerging with the overall theme of "green entrepreneurship."

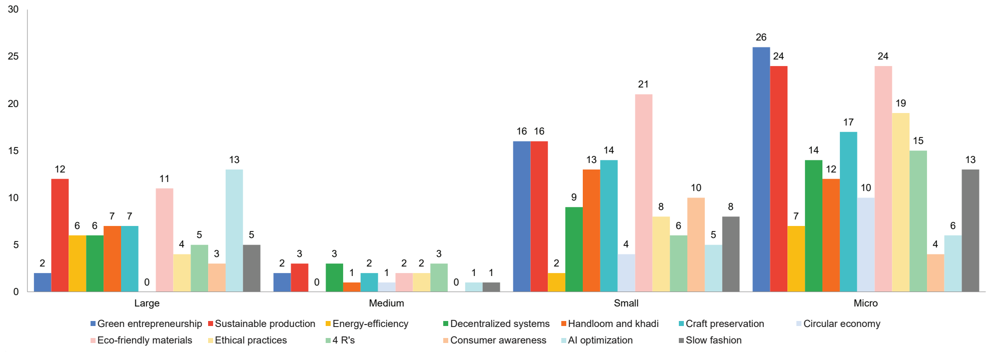


Figure 4: Comparative frequency analysis of sustainable strategies employed by different sizes of enterprises

While comparing different business formats (Figure 5), social enterprises are employing ethical practices for social impact. Sustainable production processes are followed by all businesses. Primarily, textile businesses are emphasizing energy efficiency and reducing their carbon footprint, while other types of businesses are not prioritizing these measures. Social enterprises, retail supply chain platforms, and traditional craft-based apparel businesses are able to implement decentralized systems and artisan upliftment.

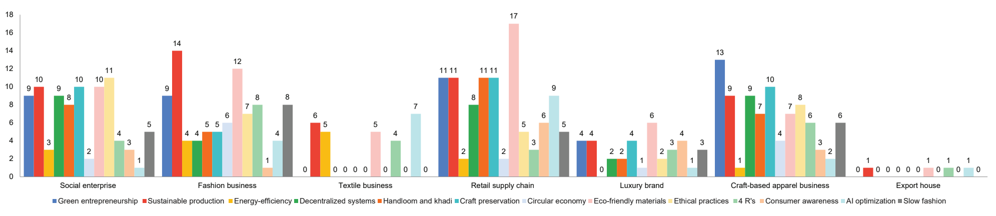


Figure 5: Comparative frequency analysis of sustainable strategies employed by different format of enterprises

Conclusion

Environmental concern, cultural preservation, and social impact are popular elements in Indian sustainable fashion and textile practices. This research shows a multi-dimensional resolution driven by green entrepreneurship, ethical production models, AI innovation, and the revival of handloom and khadi. The thirteen themes show a rising ecosystem that emphasizes sustainability, artisan empowerment, and consumer awareness. On one hand, grassroots social organizations like SEWA empower rural women, and on the other, high-tech firms like Welspun and Arvind Limited optimize production with AI. Each of these contributes to sustainability for the Indian businesses.

It is important to revive traditional crafts and decentralized production methods to establish supply chain resilience, maintain cultural identity, and assure equal economic participation, not to romanticize but as a strategic path. The rise of conscious fashion brands and eco-labels indicates a shift in consumer behavior and hence gradual systemic transformation. The Indian fashion and textile industry can benefit by integrating traditional wisdom, AI technology, and inclusive growth strategies for sustainable businesses. However, enabling an environment through supportive policies, well-prepared academia, and consistent consumer awareness is mandatory for this shift to succeed.

The current analysis suggests that different sizes and formats of businesses are adopting different approaches to increase and accelerate the sustainable fashion and textile sector's growth and transformation. Favorable policies, tax incentives, subsidies, green certification, etc., can further support the industries. And these can be more strategically defined based on the size and format of the business. Varied approaches are required to introduce artisan clusters, cooperatives, and local manufacturing hubs into national textile missions to promote decentralized models. Artisans and craftsmen should be trained for sustainable design and supported with appropriate new-age technology to facilitate the development of a better product and the marketing of the same. Further channels and systems should be established for energy-efficient and circular economy facilities to manage textile waste locally. These strategies would require government support and trained professionals.

Knowledge of eco-friendly material, sustainable production methods, life cycle analysis, circularity, energy- and water-efficient processes, and ethical ways of production must be introduced in the curricula for fashion and textile design education. Young professionals should be trained to adapt tech-driven optimization and increase AI, blockchain, and IoT usage for transparent supply chains, predictive production, and waste reduction. Green startups should be encouraged through funding for green entrepreneurship that uses upcycling, plant-based textiles, waste reduction, and circularity. By executing and attaining these objectives, India may realize its sustainability aspirations and establish itself as a global leader in ethical, inclusive, and environmentally sustainable fashion systems.

References

11.11/eleven eleven, n.d. *About us*. [online] Available at: <https://11-11.in/pages/about-us> [Accessed 19 September 2025].

Adhikary, S., 2021. Break for sustainable fashion in India on the horizon as pollution, wastage concerns rise. *The New Indian Express.* [online] Available at: <https://www.newindianexpress.com/magazine/2021/jan/03/break-for-sustainable-fashion-in-india-on-the-horizon-as-pollution-wastage-concerns-rise-2243759.html> [Accessed 16 September 2021].

Aggarwal, R., Singh, H. and Krishna, V., 2024. Doodlage: contributing to circular economy in fashion. *The CASE Journal*, [e-journal] *20*(3), pp.747-766. https://doi.org/10.1108/TCJ-05-2023-0117.

Armtrong, C. and Niinimäki, K., 2014. *Empathic fashion product-service systems for sustainable development*. In Proceedings of the Global Fashion Conference, 19-21 November, pp.19-21.

Arora, N., 2023. Shifting consumers' mindset towards the growth of sustainable fashion practices in India. *International Journal of Sustainable Fashion & Textiles*, [e-journal] 2(1), pp.9-27. https://doi.org/10.1386/sft_00018_1.

Business Research Company, 2024. Ethical *fashion global market report 2024*. [online] Available at: <https://www.thebusinessresearchcompany.com/report/ethical-food-global-market-report> [Accessed 28 August 2025].

Ciarli, T., Kenney, M., Massini, S. and Piscitello, L., 2021. Digital technologies, innovation, and skills: Emerging trajectories and challenges. *Research Policy*, *50*(7), p.104289. https://doi.org/10.1016/j.respol.2021.104289.

Connolly, J. and Prothero, A., 2008. Green consumption: Life-politics, risk and contradictions. *Journal of Consumer Culture,* [e-journal] 8(1), pp.117–145. https://doi.org/10.1177/1469540507086422.

Corbett, J., Dennehy, D. and Carter, L., 2023. Introduction to the special section: digital innovation for social development and environmental action. *Communications of the Association for Information Systems*, 53(1), pp.22-41.

Cotton Corporation of India, 2024. *Annual report 2023-24*. [pdf] Available at: <https://cotcorp.websteptech.co.uk/storage/Annualreports/Annualreports_687e0599ca0a9.pdf> [Accessed: 19 September 2025].

Ellen MacArthur Foundation, 2017. *A new textiles economy: redesigning fashion's future*. [online] Ellen MacArthur Foundation. Available at: <https://www.ellenmacarthurfoundation.org/a-new-textiles-economy> [Accessed 29 August 2025].

Ethicus, n.d. *About us*. [online] Available at: <https://www.ethicus.in/pages/about-us> [Accessed 17 September 2025].

Fashion Revolution, 2023. *Fashion transparency index 2023: how transparent are 250 of the world's largest fashion brands?* [online] Fashion Revolution. Available at: <https://www.fashionrevolution.org/fashion-transparency-index/> [Accessed 19 September 2025].

Huggard, E. and Choudhary, P., 2025. Decolonizing fashion brand sustainability narratives, In: Huggard, E., (ed.) *Creating Responsible and inclusive fashion brand narratives: theory and practice*. 1st ed. London: Routledge.

Indian Textile Journal, 2021. Welspun India launches wel-trak 2.0 blockchain, *Indian Textile Journal*, [online] Available at: <https://indiantextilejournal.com/welspun-india-launches-wel-trak-2-0-blockchain-4/> [Accessed 19 September 2024].

Invest India, 2024. *Textiles and apparel*. [online] Invest India. Available at: <https://www.investindia.gov.in/sector/textiles-apparel> [Accessed 17 September 2025].

Jain, S., 2020. Doodlage: reinventing fashion via sustainable design. In *Sustainability in the Textile and Apparel Industries: Sustainable Textiles, Clothing Design and Repurposing,* Cham: Springer International Publishing, pp. 241-261.

Khandual, A. and Pradhan, S., 2018. Fashion brands and consumers approach towards sustainable fashion. In: Muthu, S. (eds) *Fast fashion, fashion brands and sustainable consumption. Textile* Science and Clothing Technology. Springer, Singapore. (pp. 37-54).

Khanfar, A.A.A., Iranmanesh, M., Ghobakhloo, M., Senali, M.G. and Fathi, M., 2021. Applications of blockchain technology in sustainable manufacturing and supply chain management: a systematic review. *Sustainability*, [e-journal] 13(14), p.7870. https://doi.org/10.3390/su13147870.

Lal, N., 2020. India embraces sustainable fashion. [online] *Nikkei Asia*. Available at: <https://asia.nikkei.com/Life-Arts/Life/India-embraces-sustainable-fashion> [Accessed 18 June 2021].

Lal, R. and Rahman, Z.T., 2013. An analytical study of building green fashion and lifestyle brand with satisfaction based segmentation. *Anusandhanika*, 5(1), pp.6-15.

Liva, 2025. *Liva by birla cellulose: Liva's sustainable fibres embrace style with sustainability*. [online] Available at: <https://www.livabybirlacellulose.com/> [Accessed 19 September 2025].

Ministry of Micro, Small & Medium Enterprises, 2006. *The Micro, Small and Medium Enterprises Development Act, 2006. No. 27 of 2006*. (India). [pdf] Available at: https://www.indiacode.nic.in/handle/123456789/2013/3/A2006-27.pdf [Accessed 28 October 2025].

Ministry of Textiles, 2025. *The magic of Indian silk: from sericulture to masterpiece*. Press Information Bureau (Research Unit), 11 April. Available at: <https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/apr/doc2025411538801.pdf> (Accessed 28 September 2025).

Nainar, N., 2021. How technology weaves a stronger silk supply chain, *The Hindu*, [online] 22 June. Available at: <https://www.thehindu.com/sci-tech/agriculture/silk-agritech-startup-reshamandi-streamlines-production-from-farm-to-store/article34908586.ece> [Accessed 19 September 2025].

Nanda, T.S., 2019. From opulence to sustainability, Indian fashion gets redesigned. *The Wire Science*, [online]. Available at: <https://science.thewire.in/culture/from-opulence-to-sustainability-indian-fashion-gets-redesigned/> [Accessed 10 October 2025].

Nandi, P., 2025. *India apparel market size, share forecast 2034 – India market forecast till 2034.* Market Research Future, [online] Available at: <https://www.marketresearchfuture.com/reports/india-apparel-market-21788> [Accessed 29 August 2025].

Niinimäki, K., 2010. Eco-clothing, consumer identity, and ideology. *Sustainable Development,* [e-journal] 18(3), pp.150-162. https://doi.org/10.1002/sd.455.

Okhai, n.d. *About us*. [online] Available at: <https://okhai.org/pages/about-us?srsltid=AfmBOorKVHrXQojxFdy6YvRGaKeKQQydRHYh2gFEk9fNlBzKmSiO6iNa> [Accessed 17 September 2025].

Roy, A., 2024. Fashion innovation driven by AI: transforming design, manufacturing, and customer experience. *Applied IT & Engineering*, *2*(1), pp.1-8.

SEWA, n.d. *Self employed women's association*. [online] Available at: <https://www.sewa.org/> [Accessed 17 September 2025].

Singh, S. and Rani, J., 2021. Traditional Indian textile techniques used to upcycle and recycle textile waste. *Textile & Leather Review,*[e-journal] 4, pp.336-353. https://doi.org/10.31881/TLR.2021.29.

Statista, 2024. Ethical fashion market size worldwide 2023–2030. [online] Available at: <https://www.statista.com/outlook/emo/fashion/worldwide> [Accessed 29 August 2025]

Tata Trusts, (n.d.) *Antaran: Transforming crafts*. [online] Available at: <https://www.tatatrusts.org/topics/antaran> [Accessed 17 September 2025].

Tawiah, B., Cho, E., Ofori, E.A., Suh, M. and Fei, B., 2025. Sustainable fashion transition towards net-zero future: A review of digital and material innovations, policies and regulatory framework. *Sustainable Futures*, [e-journal] 10, p.101162. https://doi.org/10.1016/j.sftr.2025.101162.

United Nations, 2015. Transforming our world: the 2030 agenda for sustainable development. [online] Available at: <https://sdgs.un.org/2030agenda> [Accessed 19 September 2025].

Wahl, D.C., 2016. *Designing regenerative cultures*. Axminster: Triarchy Press

About the authors

Nandini Lal is a part-time doctoral scholar and full-time Associate Professor at Pearl Academy, New Delhi, with 23 years of diverse experience in industry and teaching. She ardently believes design has transformative potential and is a universal problem-solving tool. Her early stints at Arvind Mills, Shivalik Printing Limited, and ILFS Cluster Development Initiative endowed her with deep insights into the fashion, textile, and craft sectors. Driven by an unwavering desire for knowledge and personal development, Nandini transitioned from the corporate world to the academic realm at Pearl Academy. Throughout her tenure, she has nurtured a profound passion for sustainable fashion, recognizing the urgent need for sustainability in the industry. She firmly believes that infusing sustainability into fashion education will groom a new breed of professionals primed to address diverse challenges. Nandini envisions an educational landscape that molds future change leaders, making sustainable practices intrinsic to the fashion realm.

nandini.lal@pearlacademy.com

Sudha Dhingra is Professor in the Department of Textile Design at NIFT, New Delhi. She is the former Dean and has been teaching for the past three decades at NIFT. Her expertise lies in Indian crafts and world textiles. She has co-authored textbooks for Fashion Studies for CBSE classes XI and XII. She has co-edited a book, 'Textile Crafts of India,' covering the handloom traditions of northeastern Indian states, and co-authored 'Anant—Sustainability and Circularity in Indian Handlooms.' She has carried out her doctoral research on handloom weaving and natural dyeing in Bastar, in Chhattisgarh, and Kotpad village, in Odisha. Sudha is also the Director of the Centre of Excellence for Khadi, a project sponsored by the Ministry of MSME to support KVIC. The center has been set up with the objective to assist the Khadi Institutions to design, produce, and market high-quality differentiated Khadi products for the Indian and global markets.

sudha.dhingra@nift.ac.in

Balancing Heritage and Innovation: A Study on Traditional Craftsmanship and Technological Integration in Design Curricula

Chiranjeevi Reddy Gudimetla, Priya Darshini Gopal and Rajesh Kumar Gajam

Abstract

The research explores the integration of traditional craftsmanship with modern technology in design education. Technology's rapid evolution presents opportunities and challenges for educators seeking to balance cultural heritage with innovation. The study aims to evaluate the current integration of traditional craftsmanship and modern technology in design education in India, focusing on identifying key challenges and opportunities educators encounter when teaching these diverse skills. The objectives are to evaluate this integration, identify obstacles and possibilities in integrating traditional crafts with modern technologies in the curriculum, and make curriculum development recommendations. Quantitative and qualitative data were collected to meet study objectives. A survey was administered to 65 seventh-semester students enrolled in NIFT Accessory Design, Textile Design, and Fashion Design programs. In addition, 15 senior faculty members with over 10 years of experience, 15 alumni with about five years, and 15 senior industry executives with over 15 years were interviewed in-depth. The research demonstrates the significance of traditional workmanship and a mounting need for technology integration in the curriculum. Despite giving importance to traditional craft skills, just 21 percent of students rate instruction as outstanding. Conversely, only 8 percent of students feel highly proficient in modern technology. To bridge the gap between academic preparation and industry expectations, alumni and industry professionals emphasize a curriculum that blends conventional skills with contemporary practices. Senior faculty members stress the need for a unified curriculum that promotes creativity, technical skill, and cultural knowledge. The study culminates in the development of the CRAFTECH framework. This holistic and future-oriented model integrates strategic themes, focus areas, and curriculum directions to effectively address evolving challenges in design education. The study indicates that design education must adapt to a rapidly evolving industry to prepare students for both traditional and modern design challenges. This balanced approach is necessary to prepare future designers for a globalized and technology-driven industry.

Keywords: Traditional craftsmanship, modern technology, fashion education, curriculum development, craft-tech integration

Introduction

Design education is undergoing a profound transformation through evolving technological advancements that are reshaping creative practices and pedagogical priorities. The integration of digital tools such as CAD software and AI-based platforms to AR/VR has expanded the possibilities in the design landscape. However, this technological evolution presents critical questions about the position of traditional craftsmanship, especially in regions with rich artisanal legacies like India. While global institutions are embracing interdisciplinary, tech-driven curricula, the need to balance innovation with cultural continuity has become more urgent.

The long-standing legacy of Indian crafts, such as handloom weaving, metal casting, and folk art, embodies sustainable, community-based practices and indigenous knowledge systems. Nevertheless, these practices often remain disconnected from mainstream design education, which tends to mirror Western pedagogical models. The literature review explores how global and Indian institutions are responding to the challenge of integrating traditional and digital approaches. It examines case studies, identifies systemic gaps, and highlights emerging hybrid models that demonstrate the potential of co-creation, interdisciplinary methods, and context-driven curricula. The review sets the foundation for rethinking how design education can evolve meaningfully and inclusively.

Global shifts in design education: integrating technology and tradition

The rapid growth of technology has significantly influenced the way design is taught and practiced. It has created opportunities and challenges in blending traditional craft skills with digital tools. Integrating technology into design education expands creative possibilities but also reshapes pedagogical strategies. In this context, ‘technology’ refers to a spectrum of digital tools and systems, such as CAD software, AI-based design platforms, virtual and augmented reality, IoT, and digital fabrication techniques like 3D printing and laser cutting (Jenny et al., 2022). ‘Technological integration’ thus implies more than mere inclusion but pedagogically driven applications that complement traditional design processes (Riikonen, Seitamaa-Hakkarainen and Hakkarainen, 2020). Rather than serving as add-ons, these tools must be purposefully rooted within curricula to enhance, not replace, the depth and value of traditional design practices. This necessitates thoughtful integration where digital proficiency and material sensitivity are cultivated in tandem, supporting a more holistic and future-oriented design education.

In visual art education, Asare et al. (2023) blend traditional and digital art techniques; while traditional methods enhance tactile skills and emotional connections, digital techniques offer greater convenience and efficiency. These are initiatives to integrate craft and technology with examples like Tamara Anna Efrat's "Encoded Craft" merges embroidery with algorithmic coding and 3D printing, showing how digital methods can recontextualize heritage. Ma and Wang (2022) reveal the potential of 5G technology in revitalizing traditional metal crafts. Institutions like the University of the Arts London encourage exploration of smart textiles and material innovation alongside traditional processes, fostering sustainability and socially engaged design. Wang and Li (2022) note that advanced technologies like CAD, AI, and 3D printing boost students' creativity and digital literacy. Kazlacheva et al. (2018) emphasize the benefits of AR/VR in fashion education, enhancing visualization and interactivity. H&M's Metaverse Design Story, developed with the Institute of Digital Fashion, exemplifies digital fashion's immersive potential. Karakul (2022) supports the role of virtual learning environments in preserving craftsmanship while fostering innovation.

Marshall (2008) suggests a hybrid curriculum combining tradition and technology to meet the needs of evolving creative sectors. The Rhode Island School of Design (RISD) established the Computation, Technology, and Culture (CTC) department in 2025, integrating studio learning with emerging tech, an interdisciplinary approach, and ethically grounded design education. The Royal College of Art (RCA) has transformed from a traditional arts school to a leader in STEAM (Science, Technology, Engineering, Art, and Mathematics)-based, interdisciplinary design education.

Gaps and global parallels

India's centuries-old craft heritage, shaped over time, reflects its vast cultural, social, and historical diversity. Crafts like Banarasi silk, Kanjivaram sarees, Madhubani painting, Pashmina weaving, Dhokra metalwork, and Bidriware exemplify sustainable, community-driven practices based on indigenous knowledge systems. Unlike the West, where traditional crafts often remain confined to museums, Indian crafts thrive through intergenerational transmission within artisan communities (Economic Times, 2025). Despite its craft-rich heritage, Indian design education remains largely influenced by Western pedagogies, often marginalizing indigenous knowledge systems. Educators argue for a shift beyond Eurocentric models to include local expertise and community-driven practices (Bahl, 2024).

The key concern is limited collaboration between academic institutions and the craft sector. Indian students seldom encounter models that integrate traditional craftsmanship with modern design thinking. Japan, by contrast, offers integrated models like “Craft × Tech,” which merges heritage with innovation and connects education with industry (Swissnex, 2025). Although India is witnessing the rise of hybrid initiatives as isolated examples, such as digital archives of Uttarakhand’s crafts, these remain underfunded and lack institutional support (Chaudhary et al., 2024) compared to Japan’s coordinated efforts.

In the 21st century, there are emerging pedagogical models that emphasize blending traditional knowledge, sustainable practices, and multi-dimensional learning. Narasimhan and Mahajan (2023) advocate for co-creation in pedagogy, blending traditional crafts with sustainable practices. Xi, Ma and Ou (2024) demonstrate successful integration of academic research and industry collaboration through a micro-major in interaction design. Sood and Sharma (2023) underscore hands-on learning to promote sustainability and cultural integrity. Jha (2022) promotes rhizomatic learning in online craft education, enabling exploration of themes like indigenous knowledge, cultural appropriation, and sustainability, advocating for an inclusive, multidimensional learning approach. Meyer and Norman (2020) call for a paradigm shift from skill-based to systems-thinking design education. Reviewing institutions like RISD, Parsons, RCA, and SCAD, they conclude that most curricula remain overly discipline-specific with limited emphasis on collaboration and human-centered design. Addressing this gap is essential for equipping students to face the complex, socially and environmentally entangled challenges of the 21st century.

Educators now face the challenge of preserving craft traditions while preparing students for tech-centric industries (Risatti, 2007; Walker, Evans and Mullagh, 2019). Reddy (2014) emphasizes the necessity of synthesizing art, technology, and management in fashion education. Innovative curricular models must ensure adaptability while maintaining cultural depth. Reddy (2023) observes that Indian educators often prioritize efficiency over creativity, demonstrating the importance of rethinking pedagogical approaches. In contrast, Massachusetts Institute of Technology’s Art, Culture and Technology (ACT) program fosters experimentation, critical theory, research-driven practice, contextual inquiry, and interdisciplinary practice, thus inspiring creativity in both students and faculty.

Infrastructural disparities and lack of funding hinder progress. While global institutions adopt AI, VR, and digital tools, many Indian design schools, especially in rural regions, lack access to these technologies (Economic Times, 2025). The fact points out the importance of investments and curricular reforms that enable equitable technological integration.

Research Objectives

Based on the literature review, there is a clear need for a balanced integration of traditional craftsmanship and modern technology within design education curricula. Identifying the key challenges and opportunities in achieving this integration is essential for developing effective, future-ready educational models. Strategic and evidence-based recommendations are crucial to guide curricula reforms that foster both cultural continuity and technological adaptability.

This research aims to assess the current integration of traditional craftsmanship and modern technology in Indian design education, identify key challenges educators face, and explore opportunities for enhancing this integration. The study recommends a curriculum model that balances craft and technology inputs in design education.

Research Methodology

To meet the objectives of the study, both quantitative and qualitative data were gathered. Quantitative data were collected through a survey administered to 65 students from the Accessory Design (22), Textile Design (21), and Fashion Design (22) departments at NIFT. Out of all the NIFT campuses, one was selected through convenience sampling. Within this chosen campus, a purposive sampling strategy was applied to select a relevant student cohort. Subsequently, a census approach was used to survey all willing and available students from that specific cohort, which comprised approximately 95 students. All participants were in their seventh semester and had completed an 8-week industry internship.

A comprehensive closed-ended questionnaire was employed to understand the perceptions of design students regarding the integration of traditional crafts and modern technology in their education. Each question was framed using a categorical scale, predominantly utilizing five-point Likert-scale options. 15 multiple-choice questions made up the questionnaire, which was designed to gather answers in several key thematic areas that were in line with the study's overarching goals. These included opinions about traditional craft education, exposure to contemporary technology, curriculum balance, skill readiness, and industry relevance. A pilot study with five participants was conducted to assess the items' coherence, relevance, and intelligibility. The necessary modifications were made in response to the feedback to enhance the instrument's general validity and usability.

In-depth interviews were conducted with 15 senior faculty members from the three design departments at NIFT. These members were chosen for their over 10 years of academic experience, involvement in curriculum reviews and development, and their blend of theoretical and practical design expertise. Interviews were also held with 15 alumni, each with approximately five years of professional experience, to explore their transition from academic knowledge to professional practice. Additionally, 15 senior industry professionals, including designers, manufacturers, and other senior management stakeholders with over 15 years of experience, were interviewed. These in-depth interview questions are intended to identify areas where the curriculum needs to be enhanced, understand skill gaps among recent graduates, and evaluate how well the institution mixes traditional craftsmanship with modern technical skills.

Quantitative analysis involved descriptive statistical techniques to identify patterns in students' exposure to both traditional and technological skills. Initially, a correlation analysis was conducted to examine the relationship among Accessory Design, Textile Design, and Fashion Design students. The results are presented using stacked bar and doughnut charts.

Qualitative data were analyzed through thematic analysis of interview transcripts to uncover major themes. An inductive thematic analysis was used to examine the qualitative data, allowing codes and themes to emerge naturally from participant interviews. The study followed Braun and Clarke's (2006) six-phase process: becoming familiar with the data, manually creating initial codes, identifying recurring themes, repeatedly reviewing themes, defining and naming them, and finalizing the report. Initially, 247 codes were identified in the transcripts. After cleaning and combining similar codes, the number was reduced to 128 unique codes, which were further refined to 92. These codes were then organized into a master list of 55, which were grouped into six main themes. All coding and categorizing operations were performed manually to preserve contextual sensitivity and promote a profound connection with the data. To augment the credibility and reliability of the thematic structures, stringent validation procedures were implemented, including peer debriefing sessions for the critical review of coding frameworks and thematic interpretations by fellow researchers, as well as member checking, in which select participants were consulted to verify the accuracy and relevance of the identified themes. Reflexive journaling and comprehensive audit trails were upheld during the analysis process to record analytical conclusions, ensuring openness and consistency in theme development.

Results and Discussion

This section presents the findings of the integration of traditional crafts and modern technology in design education. The subsections cover a correlation analysis of student perceptions across disciplines, followed by an exploration of student, alumni, industry, and faculty perspectives. Each subsection offers insights into the current state of education and the evolving needs of the industry.

Correlation analysis of students' perceptions of traditional craft and modern technology integration across academic disciplines

A Spearman's rank-order correlation analysis was done to measure the strength and direction of association between the responses of the Accessory Design (AD), Textile Design (TD), and Fashion Design (FD) student groups across all educational metrics. These metrics included both traditional craft-related views (like how well students are taught, how important they think the subject is, and how much focus is put on it in classes) and modern technology-related views (like exposure, proficiency, training opportunities, and industry demand).

The correlation results indicated strong positive links between AD and TD (0.83), AD and FD (0.89), and TD and FD (0.93). This shows that, even though there were some small differences, there was a strong pattern in how the three groups ranked the value and suitability of traditional and technological inputs in design education. These findings indicate a high level of consistency in the rankings of responses across these groups. Accordingly, all groups' data were combined for further analysis. A descriptive statistical analysis was then performed to provide a detailed summary of the collective perspectives.

Students' perceptions of the integration of traditional craft and modern technology in design education

The descriptive statistical analysis of student perceptions related to Traditional Craft Skills (TCS) and Modern Technological Skills (MTS) is shown in Figure 1 as a stacked bar chart. These skills involve creating objects by hand, often using traditional techniques and materials, and they are a vital part of cultural heritage. Modern Technological Skills (MTS) encompass a broad range of areas, including software proficiency, user experience (UX) and user interface (UI) design, digital marketing, and emerging technologies like artificial intelligence (AI) and virtual/augmented reality (VR/AR). The findings reveal a strong appreciation for traditional craftsmanship, with 97 percent acknowledging its importance in education. Despite this, only 21 percent of the students rated the quality of instruction in traditional crafts as very positive, suggesting a need for improved curriculum focus in this domain.

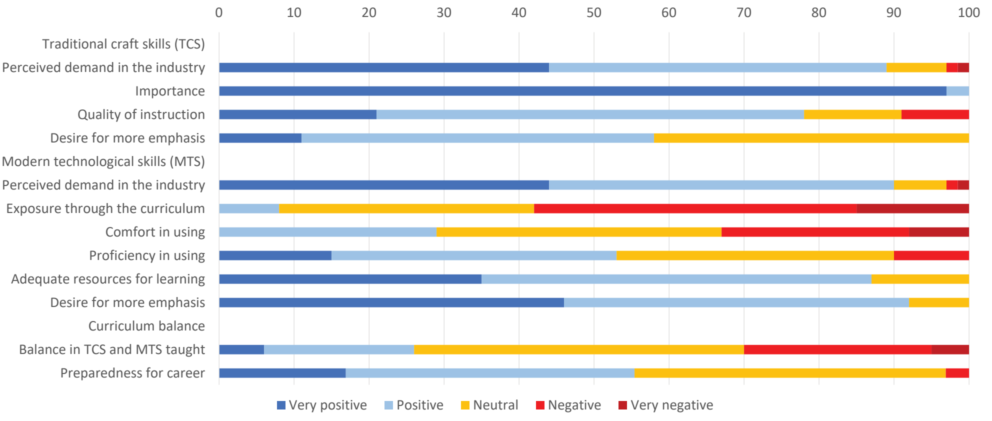


Figure 1: Perceptions of students on the integration of traditional craft and modern technology in the curriculum

The survey results indicate that students have conflicting opinions about contemporary technologies. While 67 percent of respondents expressed comfort in using digital tools, only 8 percent rated technology exposure in the curriculum as very positive, and a meager 15 percent confirmed actual proficiency. Additionally, 46 percent of the students expressed more emphasis on building technological skills through the curriculum, and just 35 percent were very satisfied with the learning resources available in the institute. These findings imply that, although students are typically at ease using technology, there is a disparity in their knowledge and the availability of sophisticated resources. Furthermore, 90 percent of students acknowledged the growing need for technology abilities in the industry, and 89 percent of students believed there is also a substantial demand for traditional artisan skills. This emphasizes the growing importance of both craft and technological proficiency in design education. The survey points to the need for better institutional support in advanced technology training and regular curriculum updates and pedagogy enhancements that balance traditional and modern skills, ensuring alignment with educational goals and industry demands.

Alumni perspectives on traditional crafts and modern technology in design education

The alumni pointed out the vital role of traditional craftsmanship in design education, particularly in fostering a deep understanding of materials and cultural heritage. As one alumna expressed, "Traditional craftsmanship skills are crucial, but the market is changing, and so are people's preferences. We must adapt by blending traditional methods with modern design trends." This perspective underscores the need to evolve traditional practices while maintaining their core values, emphasizing that while traditional skills are the bedrock of design education, they must be dynamic to remain relevant.

The alumni recognized the importance of AI, 2D and 3D CAD, IoT, AR, and VR on modern design processes and stressed their integration. A graduate said, "Modern technology, such as CAD and computer design tools, is becoming indispensable." One said, "Because of modern technology, traditional people are also moving into the modern world, speeding up their work without losing their craft." These comments point out that there must be a balanced approach that uses technology without undermining traditional crafts. Another alumna said, "Updated technologies are essential for traditional crafts to stay relevant, but not at the cost of losing authenticity."

A recurring theme among alumni was the need to address the gap between academic training and industry demands. They advocated for incorporating more industry-focused projects and practical experiences into the curriculum to bridge this gap effectively. An alumna emphasized, "Innovation and practical application should be at the forefront." Another alumnus noted, "By introducing practical skills like digital marketing and social media marketing, we can better prepare students for the industry." Another alumnus emphasized, "Focusing on the 7Ps of marketing and SWOT analysis will help designers better understand the industry."

Additionally, alumni stressed the importance of enhancing technological proficiency alongside traditional skills. They recommended the development of dedicated modules on emerging technologies and increased hands-on experience with these tools. One alumna suggested, "The current education system does not adequately prepare students for careers in design. There is a need for curriculum improvements." Another alumna added, "We need more focused training on new technologies to ensure we are not only skilled in traditional methods but also adept at using cutting-edge tools." This highlights the need for a curriculum that prepares students for current and future industry challenges, ensuring they can navigate both worlds successfully. Overall, the alumni emphasized the need for a balanced design education that combines traditional skills with modern technology, showing how the industry is changing while still honoring cultural traditions.

Industry perspectives on traditional crafts and modern technology in design education

The industry experts consistently affirmed the enduring significance of traditional craftsmanship in design education. They emphasized its crucial role in developing a profound understanding of materials, processes, aesthetics, values, empathy, social design, and sustainability. This comprehensive knowledge will not only aid in creating meaningful and impactful designs but also foster each student's unique style and creative expression. While modern technologies are crucial for precision and repetitive tasks to maintain consistency, traditional crafts hold equal significance for their distinctive imperfections, skilled craftsmanship, and natural qualities. As one expert highlighted, "Traditional craftsmanship remains vital; it provides a foundational knowledge that modern technology can enhance. The key is to blend these elements to stay relevant in our rapidly evolving industry."

The industry experts increasingly acknowledged the role of modern technology in design education. Modern technologies are transforming creative processes and enhancing efficiency. As one expert remarked, "Technology allows us to enhance traditional crafts, making them more accessible and relevant in today's market. It's not just about efficiency; it's about expanding the possibilities of what can be done with traditional techniques." However, there was a consensus that technology should complement, not overshadow, traditional skills.

A significant concern among experts was the existing gap between academic training and industry requirements. They advocated for incorporating more industry-focused projects, hands-on experiences, and professional skills into the curriculum. As one expert noted, "To effectively prepare students, we must bridge the gap between academic theory and industry practice by embedding real-world projects and essential professional skills into the curriculum." This insight shows how important it is to prepare students to manage both traditional and modern parts of the design industry, using thoughtful leadership and taking responsibility for it.

The industry also stressed the importance of a curriculum that adapts to its diverse needs. Fast fashion prioritizes technology and cost-efficiency, while high fashion values craftsmanship, necessitating a nuanced approach. One expert suggested, "Integrating elements such as research culture, sustainability, and brand positioning into the curriculum is essential for equipping students to navigate the complexities of today's design industry." This recommendation aims to create a curriculum that balances technological innovation with a strong appreciation for traditional craftsmanship.

Academia's perspectives on traditional crafts and modern technology in design education

The senior faculty members emphasized the significance of traditional craftsmanship in design education, not only for its technical skills but also for fostering cultural identity and aesthetic value. As one faculty member noted, “Traditional craftsmanship is not just about technique; it’s a key to understanding cultural narratives and aesthetic values. We must ensure these skills are seamlessly integrated into our modern design practices.” This lays the premise for the importance of preserving traditional crafts as fundamental to design learning, offering comprehensive perspectives on materials, textures, traditional wisdom, and human-centered design.

Concerns were expressed regarding the existing curriculum’s fragmentation, which frequently teaches contemporary technologies and traditional crafts separately. The necessity for a more unified strategy that crosses this gap was emphasized by the faculty. “We have a problem with curriculum organization since traditional and modern components are frequently handled as distinct things. To create designers who are skilled in both fields, a more integrated approach is required,” said a senior faculty member.

To improve students’ employability and flexibility in various industry contexts, faculty members supported curricula that incorporated future-ready skills. For both present-day use and future prediction, modern technology is essential. One professor claimed that precision and creativity require the integration of CAD, 3D printing, and virtual reality. The faculty recognized the continuous difficulties in establishing smooth cooperation between craft clusters and contemporary infrastructures when creating and executing the curriculum, notwithstanding the obvious benefits. “Creating a curriculum that effectively combines traditional and modern skills is essential, but it requires overcoming significant challenges and resistance from various stakeholders,” a different professor stated.

Stakeholder acceptance and readiness are key factors in successful integration. Traditional crafts may not resonate with students, particularly those from urban regions. Although they frequently require extra training to adjust, craftspeople are typically receptive to new technologies. Effective integration requires addressing these issues and allocating sufficient resources. “We must address the disconnect some students feel towards traditional crafts and ensure that artisans are equipped with the necessary training to embrace new technologies,” emphasized a senior faculty member. Only then would it be possible to successfully incorporate both modern and traditional features into design education.

Overall, the consensus among senior faculty was clear: a curriculum that effectively integrates traditional craftsmanship with modern technology preserves cultural heritage and equips students with the skills needed to thrive in a rapidly evolving design landscape. “The balance between age-old craftsmanship and modern technology in design education is often leaning towards advanced technology. While technology is essential, neglecting our heritage and traditional skills can lead to a lack of depth and understanding of fundamental design thinking," observed one faculty member, stressing the importance of maintaining this balance.

Categorization and thematic synthesis of findings

The interview transcripts and student survey responses were reviewed repeatedly to gain thorough familiarity with the data. Initial codes were generated manually and iteratively using key phrases and sentiments expressed by the participants. These codes were then clustered into six key themes aligned with the study's objectives: Traditional Craft Value, Modern Technology Adoption, Curriculum Balance, Craft-Tech Integration, Academia–Industry Linkage, and Educational Recommendations. Most of the participants mentioned that traditional crafts carry deep emotional and cultural meaning. One participant regarded it as "the soul of the design industry," while another quoted, "Traditional craftsmanship carries the stories and techniques passed through generations." These insights collectively led to the identification of the first theme, "Traditional Craft Value." The second theme, Modern Technology, was articulated through participants' recognition of the increasing relevance of digital tools such as AI, CAD, and 3D printing in contemporary design practice. One participant emphasized this shift, stating, "AI-based tools are essential in today's design processes." Participants suggested context-sensitive knowledge gap solutions, stating "technologies with language multiversality and audio-visuals to support artisan understanding" and "training the next generation of artisans who can later teach their elders." The third theme, Curriculum Balance, emerged from concerns raised by participants about the disproportionate emphasis on modern tools in design education. While modern technology is evolving and crucial, several participants pointed out the equally important exposure to traditional craft practices. The fourth theme, Craft-Tech Integration, emerged from discussions on bridging traditional and modern practices. Professionals shared ideas to make design education more practical, with many suggesting "more live projects with industries," "industry-alumni interactions," and "international sessions to prepare students for global design standards." The fifth and sixth themes, Academia–Industry Linkage and Educational Recommendations, emerged from these discussions, emphasizing the need to align education with professional requirements.

A thematic comparison of stakeholder perspectives

Analyzing viewpoints from all stakeholder groups is crucial to fully comprehending how traditional crafts and contemporary technologies are integrated into design education. A comparative overview of the opinions obtained from senior academics, industry professionals, alumni, and students across the six key themes derived from the qualitative interviews is shown in Table 1.

Table 1: Distinguished and critical insights from different stakeholders across key themes

Key Theme	Students	Alumni	Industry Professionals	Senior Faculty
Traditional Craft Value	Strongly acknowledge the relevance and express a strong desire for in-depth understanding and proper orientation.	Emphasize the foundational value of traditional craftsmanship but recognize the need for its integration with modern skills.	Value traditional crafts but stress the need for a hybrid approach that blends them with modern technologies.	Concerned about the fragmentation between traditional crafts and modern technology in the current curriculum.
Modern Technology Adoption	Express a strong desire for more advanced and frequent training in contemporary technologies.	Recognize the transformative impact of modern technologies and their growing influence in supporting craft design.	Highlight the critical role of technologies like AI and CAD and stress the importance of integrating them into education.	Stress the importance of using modern technologies to complement, rather than replace, traditional skills.
Curriculum Balance	Seek a more integrated curriculum that includes both modern technology and traditional crafts, emphasizing the latest design technologies.	Advocate for a balanced curriculum incorporating both traditional methods and modern technological skills.	Recommend curriculum updates to include practical skills and technologies essential for industry relevance.	Emphasize the need for continuous updates to curriculum and pedagogy to integrate traditional crafts with modern technology, addressing stakeholder resistance to change.

Craft-Tech Integration	Show a stronger preference for modern technology, viewing traditional skills as secondary.	Support a balanced approach where modern technology enhances rather than replaces traditional craftsmanship.	Emphasize the importance of a hybrid model integrating both traditional skills and modern technology.	Promote a well-rounded curriculum that uses an interdisciplinary approach to incorporate both contemporary technologies and traditional crafts.
Academia–Industry Linkage	Highlight a gap in practical application and industry readiness, with a need for more real-world experience.	Identify a disconnect between theoretical knowledge and practical industry application, suggesting more hands-on experience.	Note the need for more industry-focused projects and professional skill development in education, with emphasis on innovation and sustainability.	Identify a lack of practical application and emphasize the importance of real-world exposure and industry partnerships.
Educational Recommendations	Call for expanded resources and training opportunities in modern technologies.	Suggest curriculum improvements to include practical, commercial, and business skills.	Suggest adding research emphasis, hands-on learning, emerging technology, and thought leadership to the curriculum.	Propose integrating entrepreneurship capabilities and enhancing infrastructure to support curriculum integration.

Strategic framework development: translating thematic insights into the CRAFTECH model

Following the analysis of the six core themes, eight focal areas were identified to correspond with contemporary curriculum demands and developments. The transformation of six core themes into eight focal areas is grounded in both literature and practice. Traditional craft value evolved into the focal area of heritage, reflecting the integration of indigenous knowledge systems and hybrid curricula that strengthen authenticity in design education (Venkatesan, 2017; Bahl, 2024). Modern technology adaptation was reframed as a mindset shift, supported by frameworks such as TPACK and design thinking, which emphasize the need to blend creativity with digital competence (Mishra and Koehler, 2006; Bereczki and Kárpáti, 2021). Curriculum balance translated to pedagogy, anchored in experiential learning and reflective practice that position learning as both constructivist and situated (Piaget, 1973; Lave and Wenger, 1991). The theme of craft-tech integration was divided into digital tools and technological resources. The first strand relates to digitally mediated craft practices and computational design methods (Thompson, 2015; Efrat, 2023), while the second highlights infrastructure such as Fab Labs and makerspaces that enable experimental design practice (Kwon and Lee, 2023; Massachusetts Institute of Technology, 2024). Academia–industry linkage was coined as industry collaboration, drawing on models that emphasize knowledge transfer and co-creation between institutions and professional practice (Xi, Zhang and Liu, 2024; Luo and Huang, 2023). Finally, educational recommendations were separated into evaluation and social impact. The evaluation dimension aligns with constructive alignment and design-specific assessment frameworks (Meyer and Norman, 2020; Reddy, 2023), while social impact reflects a responsibility towards sustainability and ethical design, resonating with design for social innovation and co-creation approaches (Papanek, 2016; Narasimhan and Mahajan, 2023).

Consequently, the rearticulated topic areas were evidence-based and appropriate for curriculum framework development through the integration of primary and secondary data sources. To facilitate the retention and utilization of these eight critical areas by educators and curriculum developers, they were amalgamated into CRAFTECH at the core. The following abbreviations are used in this study: C for Contextual Craft Integration, R for Rhizomatic and Reflective Learning, A for Applied Technological Competence, F for Fusion Studios, T for Transdisciplinary Thinking, E for Experiential Industry Alignment, C for Community Co-Creation Labs, and H for Holistic Assessment. The CRAFTECH framework integrates traditional and contemporary perspectives to facilitate the development of curricula. It interprets the evolving requirements of design education and directs the creation of instructional initiatives. Finally, a radial structure was used to visually represent the eight themes, ensuring each one held equal importance and remained interconnected. The proposed CRAFTECH framework, as shown in Figure 2, highlights the core strategic themes that address challenges through holistic, future-oriented interventions. From the core to the periphery, it displays acronyms, strategic themes, focus areas, and curriculum suggestions.

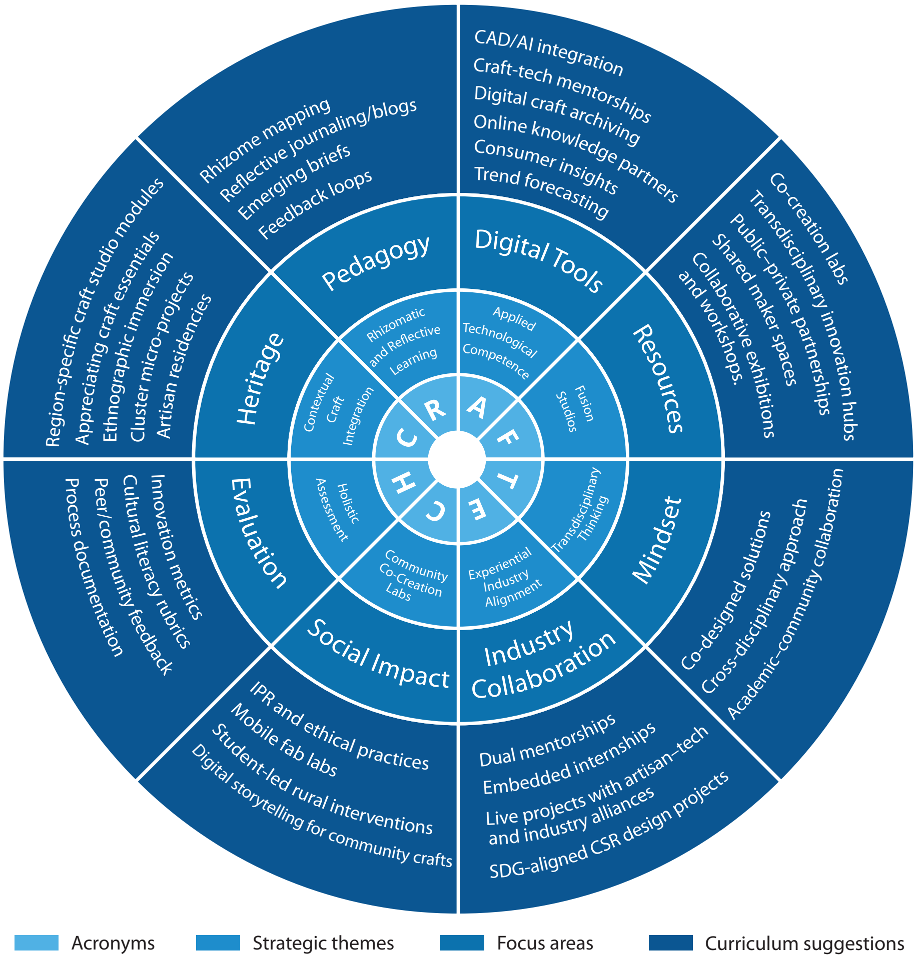


Figure 2: CRAFTECH framework

Conclusion

The integration of traditional craftsmanship and modern technology in design education is vital yet presents significant challenges. Despite 97 percent of students acknowledging the value of traditional skills, only 21 percent deemed the training in this domain adequate. Thus, there is a need felt for a curriculum that introduces effective pedagogical tools to enhance students' comprehension about traditional crafts. Further, just 8 percent of students stated that their exposure to digital tools is very satisfactory, indicating a lacuna in this domain. The results indicate a need for enhanced training and advanced-level resources because they show a gap in both proficiency and access to cutting-edge technologies.

All stakeholder groups, namely students, alumni, industry professionals, and academicians, recognized the significance of reconciling traditional craft values with technological progress, but their emphasis differed according to their roles and experiences. Students and alumni favored enhanced integration and practical experience, while industry experts and senior professors emphasized the necessity for strategic alignment with changing markets and evolving trends. These complex perspectives highlight the need for a dynamic, stakeholder-responsive curriculum that addresses disparities and promotes comprehensive development in design education.

This study resulted in the creation of the CRAFTECH Framework—a research-based, future-oriented approach that integrates traditional craft principles with modern technological skills. In conclusion, the research highlighted key concerns such as the fragmentation between traditional and modern technology, a lack of contextual relevance, limited technological exposure and resources, siloed learning, training opportunities in business and commercial skills, limited industry exposure, and a, paucity of pedagogical flexibility to integrate emerging tools with traditional practices. Addressing these gaps will be crucial for preparing students to meet the evolving demands of the design industry effectively.

Acknowledgment

The authors express their sincere gratitude to the faculty members of NIFT across various campuses for their valuable insights and support throughout this research. Special thanks are extended to the seventh-semester students, alumni, and industry professionals from the apparel, textile, and accessory fields who participated in the surveys and interviews, providing invaluable perspectives. The authors also acknowledge the senior subject experts who validated the findings at different stages, as well as their colleagues for their guidance and encouragement.

The authors used ChatGPT-4o to improve language clarity and readability, and to support comprehension of the data and emerging findings, without altering the originality or interpretation of the research content. The authors take full responsibility for the content of this article.

References

Asare, S., Walden, P., Aniagyei, E.D. and Emmanuel, M.K., 2023. A comparative study of traditional art techniques versus digital art techniques in the context of college visual art education. *American Journal of Arts, Social and Humanity Studies*, 3(1), pp.21–34. [Online] Available at:

<https://ajpojournals.org/journals/index.php/ajashs/article/view/1556> [Accessed 27 August 2024].

Bahl, D., 2024. Integration of craft and graphic design to create a new Indian aesthetic: a pedagogical experiment. *NIFT Journal of Fashion*, 3, pp.87–106. . [Online] Available at: <https://nift.ac.in/sites/default/files/2024-05/ejournal/volume-3/Article_5_DB.pdf> [Accessed 29 June 2025].

Bereczki, E.O. and Kárpáti, A., 2021. Technology-enhanced creativity: A multiple case study of digital technology-integration expert teachers' beliefs and practices. *Thinking Skills and Creativity*, [e-journal] 39, p.100791. https://doi.org/10.1016/j.tsc.2021.100791.

Braun, V. and Clarke, V., 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology*, [e-journal] 3(2), pp.77-101. https://doi.org/10.1191/1478088706qp063oa.

Chaudhary, N., Raj, M., Bhattacharjee, R., Srivastava, A., Sah, R. and Badoni, P.,2024. AipanVR: A virtual reality experience for preserving Uttarakhand's traditional art form. *arXiv preprint*. [pdf] Available at: < https://arxiv.org/pdf/2404.12643> [Accessed 16 October 2025].

Economic Times, 2025. India's design education: bridging the gap between tradition and modern innovation. *Economic Times (Education),* 29 January. [online] Available at: <https://education.economictimes.indiatimes.com/news/higher-education/indias-design-education-bridging-the-gap-between-tradition-and-modern-innovation/117682486> [Accessed 29 June 2025].

Efrat, T.A., 2023. Encoded craft: tradition meets technology in contemporary textiles. *Craft Research Journal*, 11(2), pp.78–95.

H&M and Institute of Digital Fashion, 2022. The Metaverse Design Story. [online] Available at: <https://www2.hm.com/en_in/life/culture/inside-h-m/metaverse-design-story.html?srsltid=AfmBOor2ZYX9CemCPEeavC2hBsJS3x2pp-9P_ZkHAV7PiTFtkyzGFt3T>[Accessed 30 June 2025].

Jenny, D., Mayer, H., Aejmelaeus-Lindström, P., Gramazio, F. and Kohler, M., 2022. A pedagogy of digital materiality: integrated design and robotic fabrication projects of the master of advanced studies in architecture and digital fabrication. *Architecture, Structures and Construction*, [e-journal] 2, pp.649–660. https://doi.org/10.1007/s44150-022-00040-1.

Jha, B., 2022. Crafts education and rhizomatic learning during COVID-19. *NIFT Journal of Fashion*, 1, pp.245–254. [online] Available at: <https://nift.ac.in/sites/default/files/2024-05/ejournal/volume-1/Article_14_BJ.pdf> [Accessed 29 June 2024].

Karakul, Ö., 2022. Traditional craftsmanship in architecture, conservation, and technology. In: Oksala, T., Orel, T., Mutanen, A., Friman, M., Lamberg, J. and Hintsa, M. eds. *Craft, technology, and design*. Hämeenlinna: Häme University of Applied Sciences, pp.132–148.

Kazlacheva, Z., Stoykova, V., Georgieva, K. and Ilieva, J., 2018. Application of innovative technologies in fashion design education. *IOP Conference Series: Materials Science and Engineering*, 5-7 September, Lesvos: Greece 459(1), https://doi.org/10.1088/1757-899X/459/1/012080.

Kwon, H. and Lee, D., 2023. Meta-analysis on effects of using 3D printing in South Korea K-12 classrooms. *Education and Information Technologies*, [e-journal] 28(9), pp.11733–11758.https://doi.org/10.1007/s10639-023-11644-5.

Lave, J. and Wenger, E., 1991. *Situated learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press.

Luo, X. and Huang, Y., 2023. Research on the cultivation of craftsmanship spirit among higher vocational college students and integration of industry and education. *World Journal of Educational Research*, [e-journal] 10(6), pp.33–47. 10.22158/wjer.v10n6p33.

Ma, S. and Wang, H., 2022. Cultural and creative product design method based on the fusion of 5G technology and traditional metal craftsmanship. *Wireless Communications and Mobile Computing*, [e-journal] 2022(1), https://doi.org/10.1155/2022/5634582.

Marshall, J.J., 2008. *An exploration of hybrid art and design practice using computer-based design and fabrication tools*. PhD. Robert Gordon University, Aberdeen.

Massachusetts Institute of Technology (MIT), 2024. Art, Culture and Technology (ACT). [online] Available at: <https://act.mit.edu> [Accessed 30 June 2025].

Meyer, M.W. and Norman, D., 2020. Changing design education for the 21st century. *She Ji: The Journal of Design, Economics, and Innovation,* [e-journal]6(1) pp-13-49. https://doi.org/10.1016/j.sheji.2019.12.002.

Mishra, P. and Koehler, M.J., 2006. Technological Pedagogical Content Knowledge (TPACK): A framework for teacher knowledge. *Teachers College Record*, 108(6), pp.1017–1054.

Narasimhan, U. and Mahajan, S., 2023. Textiles crafts and co-creation as a strategy for sustainable design pedagogy. *NIFT Journal of Fashion*, 2, pp.157–159. [online] Available at: <https://nift.ac.in/sites/default/files/2024-05/ejournal/volume-2/Article_9_UN.pdf> [Accessed 4 June 2024].

Papanek, V., 2016. *Design for the real world: human ecology and social change*. London: Thames & Hudson.

Piaget, J., 1973. *To understand is to invent: the future of education*. New York: Viking Press.

Reddy, G.C., 2014. Current realities and emerging trends of fashion education in India: A comprehensive study on undergraduate programmes at NIFT, Hyderabad. In: *Reflections 2014: International Conference on Fashion, Retail and Management*. 9-11 January, Hyderabad: National Institute of Fashion Technology.

Reddy, G.C., 2023. Inculcating creativity: a study on the creative abilities of educators in the field of design. In: *The Paris Conference on Education 2023, Official Conference Proceedings*. 15-19 June, Paris: Maison de la Chimie.

Rhode Island School of Design (RISD), 2025. Computation, Technology and Culture (CTC) Department Overview. [online] Available at: <https://www.risd.edu/academics/ctc> [Accessed 30 June 2025].

Riikonen, S., Seitamaa-Hakkarainen, P. and Hakkarainen, K., 2020. Bringing maker practices to school: tracing discursive and materially mediated aspects of student teams' collaborative making processes. *International Journal of Computer-Supported Collaborative Learning*, 15(3), pp.319–349.

Risatti, H., 2007. *A theory of craft: Function and aesthetic expression*. Chapel Hill: The University of North Carolina Press.

Royal College of Art (RCA), 2024. About the RCA: Vision and Strategy. [online] Available at: <https://www.rca.ac.uk> [Accessed 30 June 2025].

Sood, R.K. and Sharma, A., 2023. Sustainability in fashion and textiles education: a classroom project approach. *NIFT Journal of Fashion*, 2, pp.163–179. [online] Available at: <https://nift.ac.in/sites/default/files/2024-05/ejournal/volume-2/Article_10_RS.pdf>

Swissnex, 2025. *Reimagining traditional crafts with cutting-edge technology*. Swissnex in Japan [online]. Available at: <https://swissnex.org/japan/event/reimagining-traditional-crafts-with-cutting-edge-technology/> [Accessed 29 June 2025].

Thompson, R., 2015. Digital craftsmanship: The intersection of technology and tradition in design education. *Design Issues*, 31(4), pp.42–55.

University of the Arts London (UAL), 2024. *BA (Hons) Textile Design*. [online] Available at: <https://www.arts.ac.uk/subjects/textiles-and-materials/undergraduate/ba-hons-textile-design-csm>[Accessed 30 June 2025].

Venkatesan, S., 2017. Reviving the roots: Integrating traditional crafts with modern design education in India. *International Journal of Art & Design Education*, 36(1), pp.78–88.

Walker, S., Evans, M. and Mullagh, L., 2019. Traditional maker practices and sustainable futures: the implications of expertise. *The Design Journal*, 22(sup1), p.835-848.

Wang, B. and Li, P., 2022. Digital creativity in STEM education: the impact of digital tools and pedagogical learning models on the students' creative thinking skills development. *Interactive Learning Environments*, [e-journal] 32(6), pp.2633-2646. https://doi.org/10.1080/10494820.2022.2155839.

Xi, X., Ma, Y. and Ou, X.,2024. *Research and practice of design education through "embodied co-creation between university and enterprise"*. In: Proceedings of Asia Design and Innovation Conference, 5–6 December 2024, Shanghai, China. Beijing: Beijing University of Posts & Telecommunications.

Xi, Y., Zhang, H. and Liu, M., 2024. University-enterprise collaboration in design education: a micro-major model integrating interdisciplinary learning. *Asia-Pacific Journal of Design Innovation*, 8(1), pp.45–60.

About the authors

Chiranjeevi Reddy Gudimetla is a seasoned academic and industry professional with over 30 years of experience, including 6 years in industry and extensive academic tenure. He is a professor in the Department of Fashion and Lifestyle Accessories at National Institute of Fashion Technology, Hyderabad, and has served two terms as Chairperson. Dr. Reddy holds a doctoral degree in design education and has a strong academic foundation. His expertise spans lifestyle accessory design, design pedagogy, curriculum development, interdisciplinary student assessment, and handicraft design. He is a design advisory council member for T-Works, Telangana State Government. He also serves on the selection committee for state awards for Telangana Handicrafts Development Corporation Ltd. A prolific contributor to international conferences and workshops, he has also led faculty development programs to enhance design education. His industry roles include positions in research and engineering, and he is a motivational speaker and media contributor.

gudimetla.reddy@nift.ac.in

Priya Darshini Gopal is Assistant Professor in the Department of Textile Design at NIFT Hyderabad. She has 12 years of experience in both industry and academia, having worked at Zeba Pvt. Ltd., Arvind Mills, and the Development Commissioner of Handicrafts. At Arvind, she participated in international textile exhibitions such as Premier Vision (Paris) and Denim by Premiere Vision (Barcelona). She received the Best Couturier Award in 2018 for her fabric collections for brands like Levi’s, GAP, H&M, AEO, A&F, CK, and Zara. She holds an MA in Textiles from Chelsea College of Art and Design, where her project on contemporizing Indian traditional motifs through textile print techniques was showcased at the Battersea Affordable Art Fair, London. She also won a global motif design competition organized by Fabindia, exhibited at the Alchemy festival in London. Her research focuses on the amalgamation of technology, crafts, and sustainability in textiles.

priyadarshini.gopal@nift.ac.in

Rajesh Kumar Gajam is Associate Professor in the Department of Textile Design at NIFT Hyderabad, with 27 years of experience in industry and academia. He has been with NIFT since 2001. A postgraduate from Madurai Kamaraj University, he is currently pursuing a PhD from Banasthali Vidyapeeth. He worked for four years in Bengaluru as a Computer-Aided Textile Design (CAD) professional. His interests include Textile CAD, Graphic Design, Animation, and Visual Craft Clusters. He presented a paper on “The Need for Modernization in the Textile Industry in India through CAD” at a seminar in 2016. Kumar has served as the Craft Cluster Initiative Coordinator (2009-12) and headed the Textile Design department at NIFT Mumbai (2014-15) and Hyderabad (2016-19). He has coordinated various projects, including Tex-Styles India 2003 and the IPR Project Odisha. He has also developed course curricula and conducted training programs for NIFT faculty in Textile CAD.

rajesh.gajam@nift.ac.in

Strategic Eco-Play: Rethinking through Sustainable Design

Shivang Chauhan and Anupam Rana

Abstract

Different types of board games are created globally. Many of these games contribute to the use of plastic, wood, and paper, which affects the ecosystem of our planet. Getting rid of board games is an added burden considering the waste created and resources consumed. This research aims to address this growing issue and investigate the use of innovative product designs. A review of literature shows that sustainable design is becoming more important and popular for consumer goods. Thus, the study focuses on presenting a new way to design a board game sustainably as people become more aware of environmental issues. This innovation keeps trash out of landfills by using plastic waste to make the game board. It also encourages discussion about the power of recycling. The game pieces, made from coconut shells, promote the use of environmentally friendly materials that promote biodegradability and a better connection with nature. The goal of this research is to design a sustainable Checkers, a strategic board game using plastic waste materials, highlighting the usage of eco-friendly materials and production methods. The newly designed board game was conceptualized using the Double Diamond design process, which includes four phases: discover, define, develop, and deliver.

The developed prototype underwent user testing to assess consumer preferences for sustainable board game design and materials, as well as its effectiveness in raising environmental awareness. The redesign of the game prompted players to rethink recycling and build sensitization to the environmental impact of their choices. By bringing together sustainable materials with intentional design, the game aims to provide a practical learning experience while fostering eco-awareness.

This study points to the possibility of creating engaging and enjoyable products while maintaining environmental sustainability through integration of ecological awareness with an enhanced experience for the players. The results provide a direction in embedding sustainability in product design, thereby calling for a shift to more responsible and

eco-friendly alternatives. The study acknowledges potential concerns such as elevated production expenses, short-lived materials, and limited market attractiveness that can be addressed through further research.

Keywords: Game design, sustainability, plastic waste, eco-friendly play, environmental concern, recycling, natural materials

Introduction

In today's environmentally conscious world, integrating sustainability into everyday products, including games, is becoming increasingly significant. The use of eco-friendly materials, ethical production methods, and lasting designs encourages consumers to select products that meet their needs while at the same time minimizing the environmental impact. This approach shifts the focus from quick consumption to lasting value, aiming to redefine desirability for luxury goods (Manzini and Vezzoli, 2003; Ellen MacArthur Foundation, 2019). In fashion design, these principles might mean using organic fabrics or repurposed materials to create sustainable and unique apparel. Regarding eco-friendly home decor, one can select unique handcrafted pieces made from sustainable materials. Beautiful, sustainable products motivate individuals to acquire items that are environmentally friendly while maintaining style and functionality.

The need for sustainable game design

Across the globe, a wide range of board games, from simple to complex, are being produced and sold, catering to all ages. However, the growth of the board game sector comes at a significant environmental cost, as most games are created using resource-heavy materials like plastic, wood, and paper. According to research, the creation and disposal of board games adds to waste management problems, deforestation, and greenhouse gas emissions. Furthermore, the traditional game design approach of "take-make-dispose" supports a wasteful culture and ignores the chance to use circular economy strategies (Sharaai, Shah and Zulkipli, 2020).

Market trends in sustainable toys

According to a Verified Market Research report (2024), the green toys market size has experienced strong growth, rising from USD 22.47 billion in 2023 to an expected USD 60.14 billion by 2031. This represents a compound annual growth rate of around 12.7 percent during the forecast period 2024-2031 (Figure 1). A key trend driving this growth is the increased consumer awareness of environmental and health issues. As a result, manufacturers are moving toward biodegradable and non-toxic materials such as wood, bamboo, organic cotton, and water-based inks to replace traditional plastics. Sports and outdoor toys lead the product segment, reaching $3.91 billion in 2020, with a projected growth rate of 12.6 percent due to parent demand for active, team-based play. Dolls and action figures are also growing, particularly among five- to ten-year-olds, as parents look for engaging, educational, and collectible options. Recent research has explored consumer interest in sustainable games, indicating a rising willingness to pay more for eco-conscious products, especially among parents aged 30–45 and Gen Z consumers (ibid.). Studies indicate that sustainable attributes such as recyclable materials, ethical sourcing, and educational value are more important than brand loyalty for eco-aware consumers. A study by Peattie and Peattie (2009) revealed that aligning product messaging with environmental concerns increases consumer acceptance. Furthermore, the accelerating growth of the e-commerce market is improving access to green toys. These trends highlight a blend of environmental awareness, educational value, and new distribution methods that are shaping the future of sustainable toys (Verified Market Research, 2024).

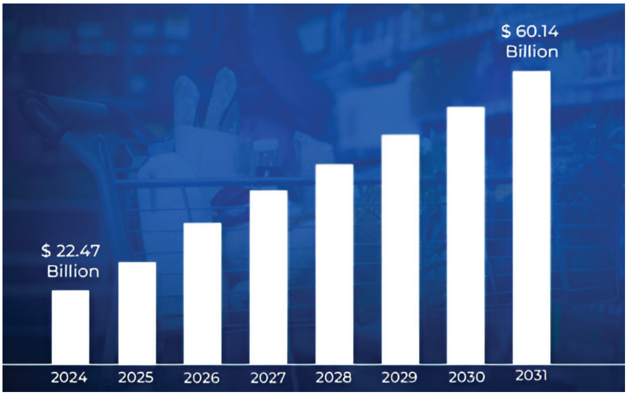


Figure 1: Green toys market size
Source: Verified Market Research, 2024

Plastic waste and repurposing

Understanding the different types of polymers, the waste management process, and the distribution elements is key to finding safe ways to turn trash into useful products to support the environment. This knowledge is vital for grasping the full extent of the problem and applying the best ways to cut down on plastic waste. Millions of recyclable or reusable plastics are incorrectly discarded. In the 1980s, only 2 million tonnes of plastic were produced worldwide. However, plastic manufacturing has greatly increased over the years, reaching about 381 million tonnes in 2015. This data shows that between 1950 and 2015, the global production of plastic garbage was about 7.82 billion tonnes (Yadav et al., 2020).

The world's toy sector uses the most plastic of any industry. According to "Environmental Impact of Toys," plastic constitutes about 90 percent of toys bought in the United States (McGrew, 2024). Plastic-made toys are a major threat to the landfills and oceans, and if nothing is done to address the issue, the situation will worsen. The planet will suffer irreparable damage if consumers continue to buy plastic-made toys and discard toys in working condition. The toy sector is one of the sectors that uses the most plastic worldwide, implying the need to identify suitable alternatives like non-plastic or sustainably manufactured toys, which will significantly lower the carbon footprint of the toy industry. It is easy to purchase different types of toys, but one does not realize the impact of the same on the environment (ibid.).

Over the past few decades, the production and use of plastics have skyrocketed. This upsurge has led to the generation of a large amount of plastic waste. Due to the limited systems to manage plastic trash, much of it becomes a part of the landfills around the globe. These landfills are a major source of plastic waste that flows out into the environment. Once released, plastic can penetrate through different areas and lead to environmental concerns. Hence, it is crucial to trace and measure plastic leaching into the environment and the ways it happens to address these issues. Plastics in the ecosystem endanger wildlife, spoil their habitats, and also pose risks to human health; for example, marine animals can get entangled in plastic, be exposed to harmful chemicals, or ingest it directly (Yadav et al., 2020). Single-use plastic (SUP) items account for half of the world's plastic production. Various methods have been employed to lessen SUP usage. Existing research often concentrates on end-of-life plastic management, such as promoting proper waste sorting and recycling to combat pollution (ibid.). However, an important strategy in building a circular economy extends beyond mere disposal to the repurposing of plastic waste to develop new, valuable items. This approach not only extends the lifecycle of materials but also provides a tangible demonstration of sustainability in action (Huang et al., 2022). This principle of transforming waste into a resource directly informs the background of the proposed board game, which is designed from repurposed plastics to exemplify this sustainable practice.

Integration of sustainable design in education

The significance of sustainable design education has escalated in recent times due to the intensifying worldwide environmental problem. Teaching students to prioritize sustainability helps them create products that meet practical needs and reduce environmental impact. Designing games with sustainable materials serves as a key platform for education and advocacy in sustainable design, creating a foundation for more thoughtful, future-oriented design practices (Lofthouse and Prendeville, 2018).

This research aims to develop an eco-friendly board game that promotes environmental awareness and responsibility. By following circular design principles and using sustainable and recyclable materials to reduce waste, this study aims to reduce the environmental impact of board games while educating consumers to think about sustainability in new ways. The study explores the appeal of sustainable design with eco-conscious choices to attract and engage consumers through visual and material appeal. The researchers attempt an “eco-play” concept by employing recycled and sustainable materials to subvert traditional board game design.

Objective

The main objective of the research is to design a sustainable “checkers game” using plastic waste and focusing on eco-friendly materials and production methods. The goal is to achieve a balance between sustainability and affordable manufacturing. At the same time, there is an endeavor to create an engaging experience that raises awareness about plastic waste and encourages responsible behavior.

Research Methodology

The sustainable checkers board game was developed using the Double Diamond design process methodology, as shown in Figure 2. The four phases of the process include discover, define, develop, and deliver. The discovery phase thoroughly examines and grasps the problem area, acquiring comprehensive knowledge and insight to direct the problem-solving strategy. Following that, the define stage amalgamates the data to accurately articulate the problem statement, structure the challenge, and understand user requirements. The development phase investigates several alternatives, followed by ideation and prototyping techniques to produce potential solutions. The final stage of the delivery process transforms ideas into functional implementations, refining and revising prototypes to prepare them for commerce. To efficiently tackle design challenges and generate substantial solutions, the double diamond model successfully balances differential and converging cognitive processes (Yenimazman, 2011).

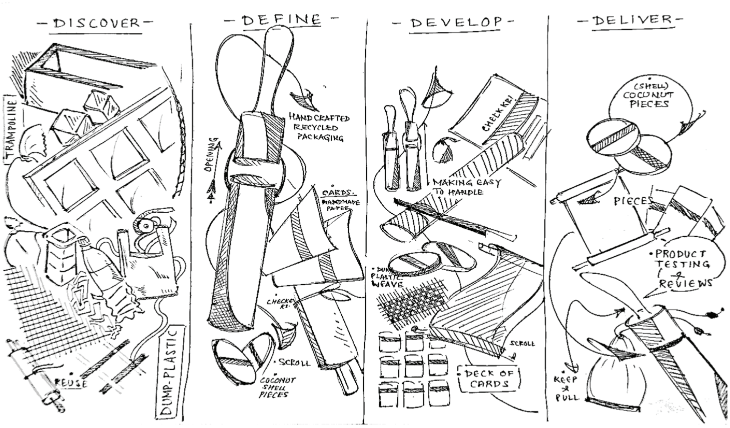


Figure 2: Double Diamond design process
Source: Shivang Chauhan

Discover

During the Discover phase, there was extensive research to understand the viability of plastic sourced from landfills and other sustainable resources for the development of a distinctive checkers game. The process commenced with the analysis of the environmental ramifications of plastic waste and the investigation of alternative materials, such as coconut shells, for game pieces, focusing on sustainable design principles. This phase entailed analyzing player behavior, market demand for sustainable products, and the technical obstacles associated with utilizing waste-derived materials. Doing secondary research and understanding the qualities of recycled materials facilitated the identification of critical concerns and opportunities for enhancing environmental awareness through an interactive educational game.

Define

In the Define phase, insights obtained from the Discover phase were combined to formulate clear design objectives. The project concentrated on developing a checkers game utilizing a woven plastic scroll for the board, coconut shell pieces, and recycled cardboard for packaging (Figure 3). The primary difficulty was reconciling sustainability with cost-efficient production while guaranteeing the game is both informative and enjoyable. This phase delineated the criteria for material procurement, production methodologies, and design elements, while concurrently establishing the overarching objective of enhancing awareness regarding plastic waste and advocating for responsible consumer practices.

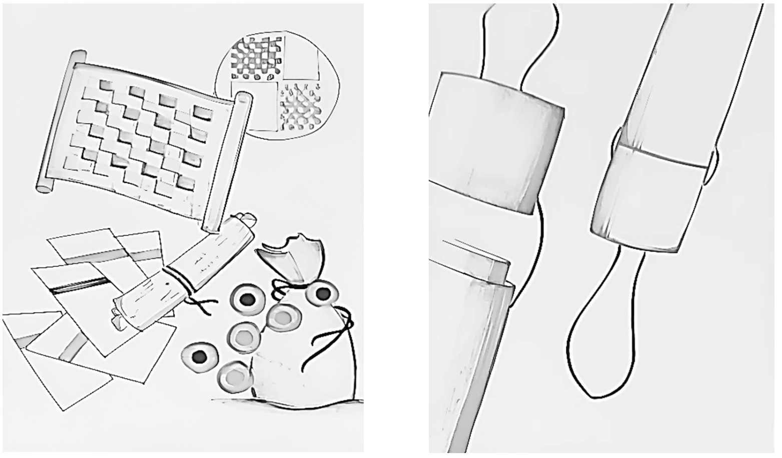


Figure 3: Product ideation
Source: Shivang Chauhan

Develop

During the Develop phase, the design concept was prototyped and enhanced according to the established objectives. Prototypes of the woven plastic scroll, coconut shell game pieces, and recycled cardboard packaging were developed and evaluated for durability, aesthetic quality, and practicality. User feedback was collected to implement modifications, guaranteeing the game is both captivating and strategically oriented, for which the strategic deck was designed as shown in Figure 4. The development phase also laid emphasis on the optimization of industrial processes to reduce environmental impact while achieving cost-efficiency objectives. Iterative design enhancements tackled potential obstacles, such as material procurement, guaranteeing the end product's feasibility and sustainability.

The materials used in developing the board game include the following:
Game board
Material: Strips of plastic wastefrom rice and grain sacks
Description: The game board's scroll format was created by weaving discarded plastic strips together.

Card deck
Material: Handmade paper
Description: 250–350 gsm handmade paper, which is the GSM range that most cards use. The deck was made out of handmade paper, which made it flexible, strong, and sustainable.

Pieces of game
Material: Shell of a coconut
Description: The game pieces were made from coconut shells, which are a natural and sustainable alternative to regular game pieces.

Packaging
Material: Repurposed cardboard
Description: The tubular packaging was made from recycled cardboard, weighing between 300 and 500 gsm. The tube was strong enough to protect the game's contents.

Thick rope
Composition: Repurposed plastic
Description: The game used plastic rope to secure the cap on the packaging.

Figure 4: Strategic deck
Source: Shivang Chauhan

Deliver

During the Deliver phase, the completed checkers game was manufactured, packed, and prepared for users with the proper specification as shown in Figure 5. The emphasis was on executing the production methods established in prior phases, which encompassed weaving plastic strips for the board, sculpting coconut shells for game components, and utilizing recycled cardboard tubes for packaging.

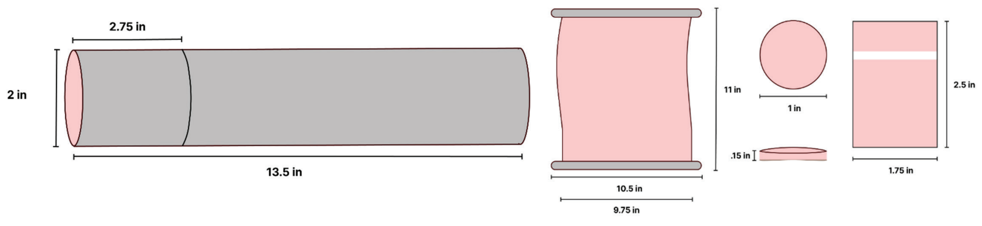


Figure 5: Prototype specification
Source: Shivang Chauhan

How to play updated checkers board game

Draughts, or checkers, is a strategic board game that traces its roots back to the ancient Egyptian game of Alquerque, which dates to around 1400 BC. Over the course of thousands of years, this game evolved and formed differently in different cultures. It is said that the board game mainly played in English-speaking countries originated in the 12th century. The game of draughts gained a lot of popularity in Europe during the 16th and 17th centuries. While it is impossible to determine when the game specifically started, it continues to thrive even today, largely due to its simple rules and complex strategies.

To enhance enjoyment of the game, additional cards were introduced. The purpose of integrating cards is to provide players with additional options beyond the standard moves available. This increases the game's versatility and encourages players to adopt a more thoughtful approach. It also demonstrates the ability to execute intelligent plays as the game progresses. The additional cards promote the concepts of planning and risk within the game, while also teaching players the idea of environmental trade-offs with phrases such as "recycle" or "skip turn." Whenever a player captures a piece from the opponent's side, a card must be played. This change promotes foresight and a more detailed approach to the game. The card deck contains a variety of cards with different values as well as some that will be valuable for future plays. This version of checkers, on average, takes longer to play compared to the standard version. The objective is to remove or obstruct all your opponent's pieces. The new version of the checkers board game is explained in more detail in Figure 6.

Figure 6: Infographic of updated checkers
Source: Shivang Chauhan

User Testing Results and Analysis

The game underwent evaluation for quality, durability, and user involvement. Packaging and branding strategies emphasize the game's ecological advantages, informing consumers about plastic waste and encouraging responsible behavior through an engaging, interactive product, as shown in Figures 7 to 10. The game is intended for both adults and children, incorporating sustainability through recycled cardboard packaging and an innovative characteristic: a portable checkers game scroll mat crafted from discarded plastic.

Figure 7: Packaging
Source: Shivang Chauhan

Figure 8: Scroll
Source: Shivang Chauhan

Figure 9: Deck
Source: Shivang Chauhan

Figure 10: Newly designed checkers
Source: Shivang Chauhan

User testing was conducted with a diverse group of ten participants, including three participants in the age group of 19–25 years and seven in the age bracket of 26 years and above (Figure 11). There were a total of five females, four males, and one as "other" to assess the game's appeal and educational impact. The overall reception was highly positive, with 80 percent of users rating the game as either 'good' (50 percent) or 'excellent' (30 percent), and 70 percent finding the rules 'easy' or 'very easy' to understand. The testing confirmed the game's significant educational value and its positive influence on players' attitudes towards sustainability. A compelling 80 percent of participants reported that playing the game increased their awareness of plastic waste, with 40 percent noting a 'very significant' impact and another 40 percent citing an 'important' one.

The enhanced awareness of the participants was directly linked to player attitudes, as demonstrated by their appreciation for the game's physical design. The most praised features were the tangible sustainable components, including the coconut shell pieces that were rated excellent by 70 percent of the respondents. This inclination was followed by appreciation for the plastic scroll mat by 60 percent of the users, and eco-friendly packaging got the maximum rating by 50 percent of the respondents. The preference for eco-conscious materials indicates that the game's core values resonate deeply with the players' own attitudes toward sustainability.

Figure 11: User testing
Source: Shivang Chauhan

In conclusion, the findings from the user testing show a successful integration of an engaging game with impactful environmental messaging. The game not only functions as an enjoyable product but also serves as an effective educational tool. Its ability to positively shift player awareness and align with pro-environmental attitudes confirms its strength in promoting sustainability.

SWOT Analysis

Based on user feedback, this game design initiative exhibits several significant strengths, primarily its environmental and educational value. Participants appreciated how the game creatively utilized innovative and natural resources. One user noted, “It’s nice to see a game that’s not only fun to play but is also good for the environment.” This appreciation also applies to the game. The introduction of a tactical card deck truly set this game apart from other tabletop games. “The card deck adds a whole new level to checkers,” exclaimed another user, adding, “It’s not just a game; it’s a strategic challenge.” This kind of feedback demonstrates that the core concept that drives the new version of the board game is quite appealing to players, merging enjoyment seamlessly with interactive play and playful environmental stewardship.

Concerns surrounding the game’s appeal and duration were highlighted in the user reports. Among the respondents, several expressed concern over the longevity of the natural elements. One user expressed the concern plainly, stating, “The coconut shell pieces are beautiful, but they look fragile, and I’m worried that my kids won’t be able to use them repeatedly.” Furthermore, the feedback suggested that the niche nature of the game may lead to a reduced audience reach. One parent commented, “While I love the eco-concept, my kids are still more drawn to their digital games." This suggests that those accustomed to online games may be reluctant to engage with the eco-friendly game concept.

User feedback provided a clear, concise overview of the opportunities and threats. The enthusiasm surrounding the board game's sustainable design indicates that the opportunity to capitalize on the growing eco-friendliness trend is significant, particularly within the educational sector. As one user remarked, "This would be a fantastic and useful tool for educators to discuss reuse and repurposing in the classroom." Conversely, the feedback on durability conveys a potential threat in the supply chain, as sourcing high-quality, resilient natural materials could be challenging and an expensive investment requiring R&D. The selection of digital alternatives exemplifies the risk of dealing with a market where sustainability does not overshadow convenience. It demonstrates the need for strategic marketing to thrive in a competitive landscape.

Conclusion

Research on developing board games sustainably identifies one of the most significant opportunities to promote eco-consciousness on everyday consumer items. The latest eco-friendly checkerboard game made of recycled plastic and natural materials, like miniature coconut shells, promotes reuse, reduces waste, and provides players with biodegradable alternatives to the traditional game pieces. The fusion of strategy and eco-sustainable gameplay enhances the entertainment value of the game and prompts players to engage with environmental challenges critically. The focus on biodegradability and eco-sustainable design commendably moves game designers and players away from the extractive, non-sustainable synthetic materials toward natural biodegradable materials. These games promote an interdisciplinary approach to design teaching through environmental problem-solving. The environmental focus of this game positively impacts the fun component and educates the players about sustainability in their everyday lives. In particular, the games promote waste reduction and the many innovative ways to achieve it, especially to younger players. The incorporation of sustainable materials aids in teaching the principles of product life cycle thinking, a core aspect of sustainable design. This is the period when some individuals contemplate the impact of their disposable items on the ecosystem. Nonetheless, issues like increasing economic costs of production, the quality and durability of materials, and limited market appeal are recognized. This research shows that designing sustainable products can be interesting and meaningful, highlighting the growing importance of sustainability in product development.

Limitations of Study

Although the research presented here effectively demonstrates that sustainability can (and should) be a part of game design, it is by no means easy. One of the limitations is the lack of comparative analysis with other sustainable products to assess the environmental impact of reusing discarded plastics and natural materials, like coconut shells, when designing games. The project leans heavily on recycling waste and natural materials. But there's not enough research on how long these materials will last and how well they'll work over time, especially in terms of how well they can stand up to repeated games. The work does not explore the technical challenges of repentance that would be required for developing sustainable games. The challenge of balancing material quality against cost-effectiveness is recognized; nonetheless, there is limited discussion on potential remedies or innovations in manufacturing methods that could improve the accessibility and economic viability of the overall product.

Recommendations

There is scope to conduct further studies to examine the production of sustainable board games, with a focus on material sourcing, quality, and production methods to achieve desirable scalability. There should be concerted efforts to conduct R&D to augment material durability and refine production processes to integrate sustainability with cost-effectiveness, guaranteeing that environmentally friendly games can compete in a wider market. Additionally, consumer research may be undertaken to comprehend market perceptions of sustainable games, thereby pinpointing measures to improve attractiveness and market share. Research comparing the environmental advantages of different sustainable materials utilized in the game, such as repurposed plastic options or biodegradable elements, may yield insights and the way forward to devise optimal methods for eco-conscious game creation.

Acknowledgment

The authors used QuillBot solely for paraphrasing purposes to enhance language clarity and readability. The tool was not used for generating ideas, analyzing data, or interpreting findings. The authors take full responsibility for the content of this article.

References

Ellen MacArthur Foundation, 2019. *Completing the picture: How the circular economy tackles climate change.* [online] Ellen MacArthur Foundation. Available at: <https://www.ellenmacarthurfoundation.org/completing-the-picture> [Accessed 19 August 2025].

Huang, J., Veksha, A., Chan, W.P., Giannis, A. and Lisak, G., 2022. Chemical recycling of plastic waste for sustainable material management: A prospective review on catalysts and processes,*Renewable and Sustainable Energy Reviews*, [e-journal] 154. https://doi.org/10.1016/j.rser.2021.111866.

Lofthouse, V., and Prendeville, S., 2018. Human-centred design of products and services for the circular economy – A review. The Design Journal, [e-journal] 21(4), pp.451–476. https://doi.org/10.1080/14606925.2018.1468169.

Manzini, E. and Vezzoli, C., 2003.A strategic design approach to develop sustainable product service systems: Examples taken from the 'environmentally friendly innovation' italian prize. *Journal of Cleaner Production,* 11(8), pp. 851-857.

McGrew, M., 2024. *Reducing the carbon footprint of plastic toys.* In: *Celebration of Student Writing 2023*. Indiana University Southeast. Available at: <https://iu.pressbooks.pub/celeb2023/chapter/28/> [Accessed 19 Aug. 2025].

Peattie, K. and Peattie, S., 2009. Social marketing: A pathway to consumption reduction?. *Journal of Business Research,* 62(2) pp. 260-268.

Sharaai, A.H., Shah, N.M. and Zulkipli, L., 2020. Effectiveness of board game and infographics on delivering life cycle assessment (LCA) concepts among secondary school students. *Journal of Wastes and Biomass Management*, [e-journal] 2(1), pp.05–08. 10.26480/jwbm.01.2020.05.08.

Verified Market Research, 2024. *Green toys market size, scope, growth, trends and forecast*. Verified Market Research. [online] Available at: <https://www.verifiedmarketresearch.com/product/green-toys-market/> [Accessed 19 August 2025].

Yadav, Y., Sherly, M.A., Ranjan, P., Tinoco, R.O., Boldrin, A., Damgaard, A., and Laurent, A., 2020. Framework for quantifying environmental losses of plastics from landfills. *Resources, Conservation and Recycling,* [e-journal] 161.https://doi.org/10.1016/j.resconrec.2020.104914.

Yenimazman, D., 2011. 'Digital experience design: ideas, industries, interaction'by LindaLeung. *Information, Communication & Society*, [e-journal] 14(5), pp.755–756. https://doi.org/10.1080/1369118X.2011.556656.

About the authors

Shivang Chauhan is currently pursuing a Bachelor of Design in Textile Design at the National Institute of Fashion Technology, Shillong. With a keen interest in sustainable design, communication design, user experience, and product design, he blends creativity with functional aesthetics. Recently, his innovative work in sustainable design was recognized with the publication of his research article, “Bamboo Play: Eco-friendly Game Design,” in the International Journal of Arts Architecture and Design. Shivang, driven by his passion to explore the intersections of design and sustainability, persistently pushes the limits of modern design thinking.

shivang.chauhan@nift.ac.in

Anupam Rana is an educator with over 24 years of experience, including 21 years in design education. He holds a BTech degree in mechanical engineering and a PhD in experience design. He spent 17 years at NIFT Gandhinagar and Shillong campuses, where he was a founding member of the Accessory Design and Experience Design program. His areas of expertise include product design, human-centric design, exhibition design, interaction design, and multidisciplinary research. Anupam also serves as an expert consultant to the industry and government organizations, bringing practical insights to academic and professional design challenges. He has presented research papers at prestigious conferences and published many articles in reputable journals. At present he is coordinator and professor of MDes in IUxD at Dhirubhai Ambani Institute of Information and Communication Technology, Gandhinagar.

anupam_rana@dau.ac.in

Reinventing Paithani Weaving: Integrating Metallic Wire for Enhanced Strength, Durability, and Contemporary Aesthetic Appeal

Neena Lokare and Sneha Bhatnagar

Abstract

Famous for its detailed motifs, vivid hues, and pure silk threads, Paithani weaving from Maharashtra is an age-old craft that exudes a sense of luxury. Yet, even with its deep cultural roots, the classic style struggles to meet the modern aesthetic demands of today's high-fashion and couture runways. This research seeks to refresh this craft by replacing the usual silk weft with a 0.8 mm copper wire inserted into the shuttle. It evaluates the impact of the metal wire on the fabric's strength, drape, and color interplay. The goal is to develop a textile that has luster like silk yet stands up to rigorous wear, giving designers a fresh, sculptural option for top-level garments.

In-depth research on traditional Paithani weaving methods was conducted to preserve the fabric's integrity while also exploring the possibility of using copper wire as weft. Copper wire was a suitable choice due to its durability and ability to develop a beautiful patina over time, increasing the fabric's value. Replacing silk with copper wire in the weft called for modifications to the traditional loom setup. Special attention was given to the tension, flexibility, and interaction between both the silk warp and copper wire to maintain the necessary flexibility for clothing while also ensuring a consistent weave. Comprehensive testing revealed that copper wire, owing to its malleable properties, achieves a balance between the rigidity required for sculptural effects and the flexibility required for high fashion, particularly in clothes tailored for a three-dimensional fit. The incorporation of metallic wire markedly improved the fabric's reflecting properties, imparting a delicate sheen akin to traditional silk luster.

The study suggests a promising result in rejuvenating traditional procedures by merging expert workmanship with modern materials, particularly in haute couture and avant-garde fashion. The final product is a fabric that preserves the legacy of Paithani weaving while providing distinctive functional and aesthetic opportunities in garment design.

Keywords: Paithani, craft, design intervention, metal wire, handloom weaving, structured form

Introduction

The Paithani sari, a quintessential and opulent fabric of India, originates from the town of Paithan in Maharashtra. Paithani weaving, praised for its deep history, detailed motifs, and bright hues, is a labor-intensive method that coalesces Indian handicraft with a distinctive weaving technique. The remarkable characteristic of this painstaking craft is distinguished by its intricate weaving method, the use of lustrous silk threads, and the vibrant traditional motifs that embellish the fabric. The main objective of this research is to examine the effect of substituting the conventional silk weft with copper wire on the structural integrity and aesthetic characteristics of the Paithani fabric. Paithani saris are made from silk; the warp is pure silk, and, though the weft too is usually silk, earlier weavers often added strands of gold or silver to create extra opulence. A signature feature of Paithani saris is the use of metal threads, usually gold or silver, woven boldly along the pallu and border, giving the fabric its rich, shiny look (Raheja and Bhagat, 2022).

A Paithani sari begins its journey on an ancient handloom called a pit loom, a manually operated loom with ancient roots. This loom's vertical warp mechanism and horizontal shuttle make it ideal for weaving the intricate Paithani patterns, which require fine craftsmanship to produce the correct textures and designs. Weaving begins with the setup of the warp strands, which are carefully placed on the loom. With multiple loom sections controlling the various colors and types of threads to achieve the necessary motifs, the threads are typically arranged to match the intended design (Mahajan, 2022). To develop the fabric, the weaver interlaces the weft threads over and under the warp threads using a shuttle. To create the finished fabric, the shuttle gradually interlaces the threads as it oscillates between the loom's two sides. The double-sided technique used in the Paithani weave ensures that the design is visible from both sides of the fabric, adding to its complexity. This is achieved by a unique technique known as "Kadiyal," in which the warp and weft threads interlace in different directions to create a fabric with the same designs on both sides. Patterns and themes such as nature, mythology, and regal symbols serve as inspiration for the traditional Paithani sari designs. Common motifs include geometric shapes, peacocks, paisleys, and floral patterns, all of which represent different aspects of Indian culture. The "Asavali" (mango or flower motif), "Kunda" (peacock), and "Shikaras" (temple) patterns are some of the most recognizable patterns. These patterns are often intricately woven, employing a method known as

"Dola," which entails alternating threads of various colors to produce elaborate motifs inside the fabric (Datta, 2021). The pallu, which is the decorative end of the Paithani sari, is the most detailed part of the sari.

Although the traditional Paithani weaving process has largely persisted throughout the ages, current weavers are progressively exploring new materials, such as synthetic fibers and metallic wires, to produce more modern iterations of the fabric. The meticulous process, involving elaborate pattern-making, double-sided weaving, and the use of luxurious materials such as silk and zari, yields a fabric that is both visually captivating and structurally complex. The Paithani sari symbolizes India's cultural heritage and artistry, and its evolution via the integration of innovative materials and techniques offers significant opportunities for the future of this revered craft.

Metallic threads have long enriched the craft of weaving. People have been using metals as strands to construct defensive mesh that can block swords and other weapons for a long time. But the metallic mesh fabric was formed of merely metal strands and was not knitted or woven into the fabric. Elena Phipps's landmark book "Woven Silver and Gold: Metallic Yarns in Colonial Andean Textiles" provides a comprehensive analysis of the influence of Spanish-introduced metallic threads, primarily silver and gilt-silver, in Andean textile traditions. Phipps (2010) demonstrated through technical study and art-historical context that indigenous master weavers adeptly integrated these metallic threads into warp and weft systems.

In the recent past different contemporary designers have focused on incorporating metal wire in weaving for varied structural and sculpted effects. Indian designer Gaurav Jain Gupta in the year 2024 used metallic yarns like copper, stainless steel, and metallic zari directly in the weaving process for his Akaaro collections instead of just putting them on the surface (Acharya, 2024). He combined these with fibers such as silk, merino wool, and khadi to create garments that were both durable and visually appealing. Metallic threads were interlaced on handlooms employing techniques such as Ikat, satin weave, and twill. This required meticulous regulation of warp tension, maintaining a steady beat, and blending metal fibers with softer yarns to ensure the cloth remained wearable. This union made fabrics that had a subtle, built-in shine, depth of touch, and architectural shape while still keeping the quality of handloom work (Aggarwal, n.d.). Another Indian designer, Rimzim Dadu, in her collection Stucco presented at India Couture Week 2024, experimented with metallic wires in her baroque-inspired collection (Chopra, 2020). The essential elements were the use of metallic hand-cut and engineered cords, with an emphasis on structure and detail. This collection demonstrates that metallic yarns are capable of producing structural shapes and remarkable couture drapes. She employed 0.45 mm fine wires, which were hand-sewn to create fabrics featuring exquisite textures and architectural silhouettes. She designed garments such as sculpted jackets, draped tops, dresses, and also stunning sarees. This was a labor-intensive process where each cord was sewn with precision in layers and tensioned to create sculptural textiles.

Selection of copper wires for weaving

In the context of utilizing copper wire as a weft thread in the Paithani weaving technique for this study, a critical decision pertained to selecting the ideal thickness. The selected thickness affects the technical viability of weaving, along with the fabric’s structural integrity, aesthetic attributes, and functionality (Mofarah, Najar and Etrati, 2018). This section delineates the parameters influencing the use of copper wire for weaving, with particular emphasis on the thickness range and its effects on the weaving process and the resultant fabric characteristics.

Factors influencing the selection of copper wire gauge

Tien Chiu, teacher and artist, has experimented with incorporating unconventional materials into the warp and weft to produce novel textures and effects (reflection, transparency, light-activated luminescence) that could be striking in wearable art clothes. Her report on “Weaving with Non-Traditional Materials” provides profound insights into material experimentation in weaving as shown in Figure 1 (Chiu, 2017). Although it does not explore profound theory, its efficacy resides in practical exploration and realistic analysis of material behavior, which is precisely the type of creative inspiration sought by several textile designers.

Figure 1: Coated copper wire, copper wire, steel-core thermoplastic woven cloth
Source: Chiu, 2017

Based on the review of the report, the following conclusions were drawn:

- The diameter of the copper wire must adhere to the suitability and specifications of the selected weaving. Traditional handlooms, which are employed for Paithani weaving, demand precise control of tension and spacing to incorporate the wire without compromising the fabric's integrity. A wire that is excessively dense may cause the fabric to become stiff, thereby hindering the natural flow of the weaving process. If the wire is excessively slender, it may lack the requisite structural integrity to create a fabric that preserves its shape, particularly in high-fashion and couture applications. The integration of copper wire into the Paithani weave substantially enhances the fabric's structural integrity and durability. Copper, being a metal, possesses greater strength than silk, rendering it an optimal selection for reinforcing the weft thread. A copper wire with a diameter of 0.6 mm to 0.8 mm achieves equilibrium between tensile strength and flexibility.

- Copper, as a metal, exhibits greater strength than silk, making it an ideal choice for reinforcing the weave thread. A copper wire with a diameter ranging from 0.6 mm to 0.8 mm attains a balance between tensile strength and ductility. These wires have adequate thickness to ensure durability while preserving the flexibility of the fabric. They provide a textile with increased rigidity, enabling the fabric to maintain its shape—a crucial attribute for couture garments that incorporate sculptural elements or form-fitting designs. The durability of copper enhances the fabric's resistance to degradation relative to traditional silk-based Paithani textiles, thereby improving its suitability for contemporary fashion applications where garments must withstand frequent use and handling.

- The aesthetic qualities and visual impact of the fabric are notably enhanced by copper wire, primarily due to its reflective surface and the patina it acquires over time. The selection of wire gauge influences the luminosity and visual quality of the fabric. Copper wires of 0.8 mm impart a striking metallic luster that enhances the fabric's elegance while emphasizing the traditional motifs of Paithani weaving—namely the asavali (flower) and kunda (peacock)—making them more prominent and three-dimensional.

Moldability and couture applications

In couture and high-fashion design, a crucial attribute of a fabric is its capacity to be molded and converted into sculptural forms. Copper wire measuring 0.8 mm in diameter facilitates the fabrication of textiles capable of maintaining three-dimensional forms, rendering it suitable for garments featuring sculptural components, such as structured gowns or avant-garde creations. This moldability is a distinguishing feature that differentiates this modified Paithani fabric from original silk Paithani, which does not possess the same structural capability for intricate, three-dimensional clothing patterns. A thicker copper wire, such as 10 mm, would yield a fabric that is significantly more stiff and able to maintain extreme shapes. Nonetheless, this may compromise the fabric's drapability and fluidity, making it less suitable for particular couture applications that necessitate a combination of rigidity and elasticity (Chase, n.d.). 0.6 mm to 0.8 mm copper wire is deemed the optimal choice for this study, offering an excellent combination of strength, flexibility, and aesthetic appeal. This thickness enhances the fabric's durability, enabling it to withstand wear and maintain its structural integrity, while also providing a lustrous metallic sheen that elevates the fabric's aesthetic appeal. This research adeptly integrates contemporary materials with traditional weaving techniques by rigorously assessing the thickness of copper wire, thus offering novel prospects for the future of Paithani weaving.

Methodology

The methodology comprised three essential components: selection of suitable materials, the weaving process incorporating copper wire, and a comparative investigation of the new fabric against conventional Paithani textiles. The project was undertaken by semester seven students in the course Craft-Based Product Development and was supported by the Development Commissioner (Handlooms) as part of the Craft Cluster Initiative of the National Institute of Fashion Technology. The authors supervised this Paithani weaving project, and the design development of this project was conducted in the Yeola Cluster of Paithani weaving. The authors, as fashion educators and scholars, have engaged with the Indian fashion industry, cultivating an understanding of the craft sector and the transformative potential of design in the same. Engagement with the institute's programs in the crafts sector offered further possibilities to comprehend traditional crafts, including the materials and processes involved, through joint projects with students and artisans. These collaborations and interactions fostered an awareness of how design may tackle the challenges of product diversity and innovation in traditional weaving techniques for advanced surface development.

The research utilizes a practice-based methodology, incorporating co-design and co-creation with craftspeople. NIFT collaborates with several textile craft clusters under the guidelines of the Ministry of Textiles for this craft-based project. Students, guided by educators, collaborate with craftspeople to co-create, generating innovative concepts and creations in modern design language. For this experiment, the students worked together with Paithani weavers in Yeola to produce new patterns and conduct surface exploration. The cluster visit lasted 5-7 days, during which the concepts were discussed with the craftspeople and modified based on collaborative conversations and their feedback. In the Yeola project, students developed surfaces and materials within the cluster and designed and constructed fabrics on campus. Following experimentation in the lab, the final samples were developed at the cluster. The objective of these initiatives was to create versatile designs for urban customers in India and beyond, with consideration for the slow fashion movement. The following sections delineate the methodologies, materials, and equipment employed in the creation of a modified Paithani fabric integrating 0.5 mm copper metallic wire as the weft and its evaluation.

Expert review

To assess the feasibility of incorporating copper wire in Paithani weaving, in-depth interviews were conducted with Ms. Bhamini Subramaniam, designer and member of Paramparik Karigar, an organization promoting and preserving Indian traditional crafts, and Ms. Savitha Suri, textile revivalist, curator, and author. The points of discussion revolved around the fabric's aesthetic and functional characteristics and the possibilities and challenges of incorporating metal wires into handloom weaving.

Material and equipment for textile weaving

This research employs pure silk threads, 0.5 mm copper wire, and zari threads (gold or silver). Each material was selected for its distinctive properties that enhance the fabric's texture, durability, and aesthetic appeal. The primary innovation in this study is substituting the conventional silk weft with 0.5 mm copper wire. Copper wire was chosen for its malleability, durability, and distinctive reflecting properties, which provide an aesthetically appealing fabric and augment its structural integrity. Copper wire, unlike silk, provides rigidity to the fabric, rendering it appropriate for the development of more structured or sculptural designs in haute couture garments (Desai, 2007). One of the steps involved coiling copper wire and winding it on small bobbins called tillis, used in the ancient Paithani weaving technique (Figure 2-3). These tillis facilitate the uniform distribution of copper wire within the fabric during the weaving process, ensuring consistency. Using these tiny tillis also prevents wire tangling and allows for smooth and easy handling of the wire during the weaving process. Zari threads, made from gold or silver metallic fibers, were added to the pallu and borders of the saree. The zari threads maintained the shiny, luxurious quality of Paithani fabrics, while the copper wire provided an additional layer to the fabric's texture and durability.

Figure 2: Paithani artisan coiling copper wire

Figure 3: Copper wire on small bobbins called tillis

The weaving process commenced with the preparation of the warp threads, which were arranged on the loom in the conventional manner with pure silk. The warp threads were carefully wound onto the loom, keeping even tension to ensure a smooth fabric while adding the weft. The 0.5 mm copper wire that was wound onto small bobbins was then placed on the shuttle of the loom for the weft to initiate the weaving. The tension of the warp threads was meticulously regulated to prevent the fabric from becoming excessively tight or loose. The copper wire was interlaced with the silk warp under regulated tension to preserve a balance between rigidity and pliability. The weaver deliberately reduced the weaving pace in contrast to conventional Paithani techniques. This facilitated improved manipulation of the metallic wire. Copper wire behaves differently than silk and requires more time to manipulate well to guarantee correct interlacing with the warp threads.

Working with copper wire in the weft required careful handling because the wire had to blend seamlessly with the silk warp while keeping the design intact. The weaving included mixing copper wire with traditional zari threads to create intricate patterns. This was done while maintaining the classic Paithani motifs, like the Asavali (mango) and Kunda (peacock), while adding new structural and visual details through the metallic wire. Special care was taken with the pallu and borders, which are the most complex parts of the Paithani saree. The pallu was crafted from a combination of copper wire and zari threads, necessitating meticulous attention to attain a uniform metallic luster from both components.

Fabric testing

The comparison between the pure silk Paithani and the experimental Paithani sample with metallic weft yarns was conducted to better understand the alterations in structure, functionality, and aesthetics resulting from the integration of metallic wire into the conventional weave.

Expert evaluation

Prototype samples of copper-infused Paithani fabric were produced on handlooms in Yeola, Maharashtra, and subsequently presented to experts for qualitative assessment. Feedback was obtained concerning the economic viability and market expansion of handloom fabrics through the integration of materials such as copper wire. The expert panel consisted of Mr. Rajesh Kumar, an exporter, handloom, and handicraft brand; Ms. Rugmani Venkatadri, an academician; Mr. Sagar Kherud, Sagar Silks; Yeola Paithani, a Paithani weaver from Yeola; Ms. Ila Ranjan, Head Designer, Suta Pvt. Ltd.; and Ms. Suchitra Dhiloria, a fashion designer.

Comparison between Modified Fabric and Traditional Paithani

Table 1 denotes the comparative chart that provides a comprehensive analysis of the performance characteristics between the traditional pure silk Paithani and the modified Paithani that includes metallic wire in the weft. Each parameter, namely drape, fabric count, weight, stiffness, resilience, and tensile strength, was assessed manually utilizing fundamental textile testing methods to preserve the authenticity and artisanal character of the research. The findings unequivocally indicate that although the incorporation of metallic yarn marginally augmented stiffness and weight, it significantly improved tensile strength, durability, and structural stability. This comparative assessment is essential to the research, as it empirically substantiates the intervention, connecting traditional handloom artistry with contemporary technological advancements, thus bolstering the study's aim of structural improvement without sacrificing aesthetic integrity.

Table 1: Comparative chart of pure silk Paithani fabric and metal wire infused fabric

Parameter	Manual technique used	Pure silk Paithani (control sample)	Modified weft metallic Paithani (experimental sample)	Observation/ Inference
Drape Coefficient (Cylinder Drop Test)	A circular cylinder was placed vertically. Fabric sample (1 m × 1 m) was centered on top. Light projected vertically downward; diameter of shadow measured to calculate drape coefficient manually.	Shadow covered ~68% of circle area – soft, fluid fall; multiple fine folds observed.	Shadow covered ~82% of circle area – broader, stiffer folds; more structured fall.	Metallic yarn addition increased stiffness and dimensional shape; ideal for sculptural forms.

Parameter	Manual technique used	Pure silk Paithani (control sample)	Modified weft metallic Paithani (experimental sample)	Observation/ Inference
Fabric Count (Manual Pick Glass Test)	A pick glass (thread counter) used to count number of warp and weft yarns per inch manually at three different areas and averaged.	96 × 72 (fine silk warp and weft)	96 × 64 (same warp, fewer wefts due to thicker metallic wire)	Metallic wire reduced weft density, slightly loosening the fabric structure.
Fabric Weight (Manual GSM Test)	Fabric sample (10 cm × 10 cm) cut and weighed on digital balance. Weight converted to g/ m².	95 g/m²	124 g/m²	Metallic yarn increased GSM, adding body and enhancing dimensional stability.
Stiffness (Handle and Cantilever Bend Test)	Fabric edge extended from a table; the overhang length measured at point of bending. Also assessed by manual touch and fold resistance.	Low stiffness; bends and folds easily.	Medium stiffness; higher resistance to bending.	Metallic inclusion enhanced rigidity, supporting form retention.
Resilience (Manual Crease Recovery Test)	Fabric folded and pressed between two glass plates for 5 minutes under 500 g weight. Time taken for crease recovery visually noted.	High resilience; recovered ~85% of crease quickly.	Moderate resilience; recovered ~70%.	Metallic weft restricted elasticity, but improved shape holding post-manipulation.
Tensile Strength (Manual Tug Test)	Equal-sized strips gripped manually and pulled along warp and weft directions until first sign of yarn breakage observed.	Warp: strong; Weft: moderate.	Warp: same; Weft: significantly stronger due to metallic reinforcement.	Overall tensile strength improved, increasing durability and wear resistance.

Conclusions derived from the comparative analysis

The comparative analysis of pure silk Paithani and metallic-weft modified Paithani indicates substantial alterations in the fabric's physical, mechanical, and aesthetic properties.

- Drapery conduct: The pure silk control sample exhibits a reduced drape coefficient, signifying enhanced fluidity, softness, and the capacity to create delicate, elegant folds.
- Fabric density and composition: The warp count remains constant as both fabrics utilize the identical silk warp. The decrease in weft density in the changed fabric indicates that metallic wefts occupy more space, resulting in fewer picks per inch.
- Fabric weight: The metallic-reinforced Paithani exhibits a notable increase in fabric weight. The elevated GSM enhances body and dimensional stability and imparts a thicker drape. The additional weight enhances designs necessitating volume or structure, whilst the pure silk sample has a lightweight quality, making it suitable for flowing, conventional draping approaches.
- Stiffness: The rigidity and grasp stiffness significantly escalate with the incorporation of metallic elements. The altered fabric exhibits greater resistance to bending than pure silk, signifying increased rigidity.
- Resilience and crease recovery: The metallic-weft fabric demonstrates diminished robustness owing to decreased flexibility. Nonetheless, this diminished recovery proves beneficial when a design necessitates the fabric to preserve pleats, folds, or molded shapes.
- Tensile strength: The warp strength is consistent across both fabrics because of the unchanged warp mechanism. The experimental sample exhibits enhanced weft-wise tensile strength attributed to metallic reinforcement, hence augmenting durability, longevity, and resistance to abrasion or stress during usage.

Findings

The prototype samples of copper-infused Paithani fabric were developed on tabletop handlooms with a weaving width of 24 inches (Figure 4). The warp comprised silk yarn sourced from Yeola, traditionally used in Paithani sarees, while the weft consisted of 0.5 mm copper wire. The final prototypes that were developed at the Yeola cluster measured one meter in length (Figure 5) and were distributed to a selected expert panel for evaluation. The objective was to assess the viability and market readiness of this innovation.

Figure 4: Sample prototype on tabletop loom

Figure 5: Metal infused Paithani samples

Professionals expressed significant interest in the durability and opulent appearance of the copper-infused fabric. Designers conveyed enthusiasm over the fabric's capacity to maintain its form and facilitate sculptural creations. This established it as a prospective transformative force in the couture and high-fashion sectors. The metallic luster and texture were commended for enhancing the aesthetic appeal of classic Paithani designs, rendering them appropriate for diverse contemporary fashion uses. Although the fabric gathered favorable reviews for its aesthetic attributes, it was crucial to evaluate how its weight could affect its practicality for routine or informal applications. Nevertheless, for couture garments and special events, the additional weight was frequently regarded as advantageous, enhancing the fabric's opulent texture and resilience.

The following summarizes the main observations from the testing of the pilot samples and feedback from experts.

- Structural integrity: The incorporation of 0.5 mm copper metallic wire in the weave significantly enhanced the fabric's structural stability. The incorporation of copper wire enhanced the fabric's durability and abrasion resistance, surpassing the capabilities of traditional Paithani sarees, primarily crafted from silk. The copper wire increased the rigidity of the fabric.
- Shape retention: A prominent feature of the copper-infused Paithani is its capacity to maintain form. This enhanced moldability was particularly beneficial for creating things that require precise outlines or distinct curves, such as couture gowns,

jackets, or avant-garde designs. The fabric's weight was considerably increased due to the use of copper wire; however, this did not adversely affect its drape or comfort. The additional weight imparted sophistication and richness to the fabric while maintaining its wearability.

- Visual result: The copper wire raised the surface slightly, emphasizing the delicate motifs typical of Paithani designs and adding visual interest. The reflective properties of the copper wire gave the fabric a shiny finish. This sheen enhanced the usual luster of silk, resulting in a fabric that sparkled and changed under different lighting. The use of traditional zari threads (gold or silver) with copper wire enhanced the opulence, imparting a rich, multi-dimensional luster to the fabric. The contemporary metallic finish, combined with the elaborate Paithani patterns, rendered the fabric appropriate for haute couture garments, where texture and visual appeal are paramount. The fabric exhibited a luxurious, modern aesthetic while maintaining the traditional intricacy of Paithani weaving, culminating in an ideal fusion of classic craftsmanship and contemporary innovation.

Analysis

Textural innovation in high fashion

The integration of 3D texture and reflective shine into the fabric offers innovative opportunities for tactile and visual design. The copper wire creates a three-dimensional impression, enhancing the fabric's sculptural quality and facilitating dynamic light interaction. This is particularly significant in evening attire or haute couture, where aesthetic appeal and opulence are essential. Paithani fabrics with metallic wire can be utilized to produce statement items, such as ball dresses, fitted suits, or avant-garde collections, where texture, luster, and structure are essential elements of the design. The integration of traditional Indian weaving methods with modern metallic embellishments promotes cross-cultural creative collaboration. Designers in major fashion capitals such as New York, Paris, and Milan may be drawn to these textiles because of their rich legacy, luxurious aesthetics, and versatility. The metallic sheen may make these materials adaptable across diverse fashion categories, including ethnic attire, modern streetwear, and haute couture collections.

Impediments and limitations

The integration of copper wire into Paithani fabric has significant promise; nonetheless, specific challenges and constraints must be resolved, especially with practical production.

The incorporation of copper wire into the weave poses a considerable issue due to the augmented weight of the fabric. Copper wire possesses significantly greater density than silk, thus augmenting structural stability, although potentially undermining the comfort of the fabric, particularly for garments designed for extended use. The fabric is suitable for couture items and formal wear; yet, its weight may make it less appropriate for casual or everyday clothing.

Complexity of production

Weaving using metallic wire requires greater precision and meticulousness. The copper wire must be handled carefully to ensure smooth interlacing with the silk warp, preventing breakage or distortion. Furthermore, the weaving speed is reduced compared to traditional Paithani weaving due to the rigid properties of the metallic wire. This may result in prolonged manufacturing times and potentially higher labor costs, hence increasing the overall expenses of fabric production. These limitations may hinder the scalability of this technology, especially for mass-market production.

Cost considerations

The utilization of metallic copper wire and requisite intricate weaving techniques increases the fabric's production cost. Copper wire is costlier than conventional silk or zari, and the protracted weaving process contributes to the overall cost. This may render the fabric less attainable for prominent fashion designers or mass-market consumers. In the luxury fashion and couture industries, where exclusivity and craftsmanship are esteemed, the elevated price may be warranted by the distinctiveness and superior allure of the fabric.

Technical proficiency

Creating copper-infused Paithani requires weavers to have both traditional weaving skills and the ability to handle unusual materials. Training to use metallic wires and incorporate them into the loom is essential. Insufficient skill development can lead to fabric damage, uneven patterns, or wire breakage. This matter underscores the necessity for specific training programs to maintain the craft and guarantee sustainable innovation throughout time. It safeguards and advances traditional crafts while fostering innovation within established techniques. Manipulating metallic wire necessitates meticulous handling and proficiency, hence augmenting the intricacy of the weaving procedure and elevating both production duration and expenses. Nonetheless, these obstacles are eclipsed by the fabric's distinctive attributes and its capacity to captivate designers and consumers who prioritize sustainability, artisanal craftsmanship, and luxury. The successful incorporation of copper wire into Paithani weaving demonstrates the capacity of traditional textiles to flourish and adapt within the contemporary fashion industry. This research establishes the foundation for a new epoch in textile production that integrates traditional craftsmanship with modern innovation, whilst respecting cultural legacy and current design. Designers must assess the comfort of materials, especially in warmer climates or for garments requiring significant mobility. This identifies an area for further research.

Conclusion

This study's findings indicate that the integration of 0.5 mm copper wire into Paithani weaving improves the fabric's durability and aesthetic quality. The copper-infused fabric exhibited enhanced durability and improved shape retention, making it appropriate for structured couture garments. The fabrics' three-dimensional texture and metallic sheen offered a modern, luxurious embellishment to traditional Paithani designs, expanding their relevance in high-fashion settings. Industry professionals and experts have largely provided positive feedback, appreciating the amalgamation of traditional craftsmanship with contemporary innovation. This research demonstrates that incorporating new materials, such as copper wire, into traditional textiles can rejuvenate the handloom industry and maintain its competitiveness in the contemporary market. The incorporation of copper wire in Paithani weaving signifies a departure from conventional techniques while yet respecting the fundamental tenets of handloom weaving. This provides weavers the opportunity to investigate and invent within specified parameters. They can advance their craft while staying true to its roots. The economic viability and market growth of handloom fabrics can improve by incorporating materials like copper wire. Handloom artists may find that creating textiles with added durability and modern appeal could attract a new group of buyers who value sustainability, craftsmanship, and exclusivity.

Incorporating copper wire into the weaving process requires skill in both traditional techniques and handling metallic materials. This could lead to the development of new skills within the handloom industry. Weavers, artisans, and textile designers can be educated in the utilization of novel materials, safeguarding traditional craftsmanship while expanding their product range. The expanding market for these textiles may stimulate the establishment of training programs, workshops, and collaborations, thus enhancing sustainability and diversity within the handloom industry. The incorporation of metallic wire in Paithani fabric presents numerous unique design possibilities in modern fashion and haute couture. Designers can investigate fabric manipulation techniques like pleating, folding, and draping, which can now be executed more effectively on materials that exhibit both visual allure and structural integrity.

Acknowledgment

The authors used QuillBot solely for paraphrasing purposes to refine language and improve readability. The tool was not used for generation of ideas, data analysis, and interpretation. The authors take full responsibility for the content of this article.

References

Acharya, P., 2024. A window into fashion Deisgner Gaurav Jain Gupta's artistic process. *Grazia India*. [online] 2 August. Available at: <https://www.grazia.co.in/fashion/weaving-stories-with-gaurav-jain-gupta-12838.html> [Accessed 27 November 2025].

Aggarwal, A., n.d. *Metallica*. Fashion Design Council of India. [online] Available at: <https://www.fdci.org/metallica/> [Accessed 27 November 2025].

Chase, R., n.d. *How to weave wire*. Instructables. [online] Available at: <https://www.instructables.com/How-to-Weave-Wire/> [Accessed 27 November 2025].

Chiu, T., 2017. *weaving with non-traditional materials*. Tien Chiu's Blog. [online] 24 May. Available at: <https://tienchiu.com/2017/05/weaving-with-non-traditional-materials/> [Accessed 27 November 2025].

Chopra, Y., 2020. Designer Rimzim Dadu on changing the tactile experience of materials through innovative cord work. Vogue India. [online] Available at: <https://www.vogue.in/fashion/content/designer-rimzim-dadu-takes-us-through-the-process-of-cord-work?utm> [Accessed 10 November 2025].

Datta, D., 2021. Paithani saris and women in Maharashtra: patterns of consumption and preference through time. *Internotional Journal of Multidisciplinary Research and Technology*, 388. [online] Available at: < https://www.researchgate.net/publication/371272156_Paithani_Saris_and_Women_in_Maharashtra_Patterns_of_Consumption_and_Preference_Through_Time#full-text> [Accessed 3 November 2025].

Desai, A.A., 2007. *Metallic fibres.* Fibre2Fashion. [online] September. Available at: <https://www.fibre2fashion.com/industry-article/2471/metallic-fibres> [Accessed 27 November 2025].

Mofarah, H.M., Najar, S.S. and Etrati, S.M., 2018. Investigating the electromagnetic shielding effectiveness of copper/cotton full Milano and 1 × 1 rib weft-knitted fabrics. *The Journal of the Textile Institute*, [e-journal] 110(6), pp.891–900. https://doi.org/10.1080/00405000.2018.1531743.

Mahajan, S., 2022. Comparative study of original paithani & duplicate paithani. *International Journal of Textile and Fashion Technology*, [online] pp.35–42. Available at: < https://www.researchgate.net/publication/362230561_COMPARATIVE_STUDY_OF_ORIGINAL_PAITHANI_DUPLICATE_PAITHANI> [Accessed 3 November 2025].

Phipps, E., 2010. *Woven Silver and Gold: Metallic Yarns*. In: Colonial Andean Textiles in Colonial Andean Textiles. Notes in the History of Art, [online] 29(3), pp.4–11. Available at: < https://www.journals.uchicago.edu/doi/abs/10.1086/sou.29.3.23208503?journalCode=sou> [Accessed 3 November 2025].

Raheja, R. and Bhagat, S., 2022. Historic Indian textiles of gold and silver. *Journal of Visual and Performing Arts*, 3(2), pp.477–494.

About the authors

Neena Lokare is a skilled fashion academician, designer, and textile enthusiast, with more than 20 years of teaching experience. She is currently Assistant Professor at NIFT, Mumbai. With a postgraduate degree in fashion management and a fashion design degree from NIFT Mumbai, she is presently pursuing a PhD in Indian textiles with an emphasis on the connections between tradition, sustainability, and modern expression. Apart from her scholarly contributions, Neena is well-known for her book 'Styling my Handloom,' in collaboration with DC Handlooms, launched on Handloom Day 2025 by Hon'ble Minister of Textiles, Shri Giriraj Singh. Neena is passionate about teaching the upcoming generation of designers to appreciate India's living textile traditions in ways that are relevant to the rest of the world. One drape at a time, she hopes to weave stories, identities, and opportunities into India's handloom legacy, making it not only relevant but also inspiring for the next generation.

neena.lokare@nift.ac.in

Sneha Bhatnagar is Assistant Professor with the Department of Fashion Design in NIFT Mumbai. She is a NIFT Gandhinagar alumna with a degree in fashion design. Her area for doctoral research is the depiction of dress and fashion in classical novels. She specializes in fashion forecasting and fashion history. Passion for design brought her to join NIFT in the year 2014 at NIFT, Patna, and she later joined NIFT Mumbai in 2018. She has worked in the industry and has been an academician now for 10 years. She specializes in the history of design, fashion and textiles, surface techniques, and craft-based subjects. She has done research in the area of craft and textiles.

sneha.bhatnagar@nift.ac.in

A Conceptual Framework Using Oscilloscope–AI Integration for Resonance and Quality Mapping in Handloom Textiles

Deepa Parameswaran

Abstract

Handmade fabrics, deeply rooted in India's weaving traditions, represent one of the most sustainable alternatives to industrial textiles. Produced with natural fibers, minimal energy, and eco-friendly dyes, they mitigate emissions, conserve water, and preserve heritage. India, as the world's largest handloom producer, holds a unique responsibility and opportunity to scale this sector as both a climate solution and rural economic engine. Strengthening handlooms is therefore not only an environmental imperative but also a pathway for equitable livelihoods and cultural resilience. Beyond ecological significance, handmade fabrics are emerging as carriers of vibrational resonance. Early analysis suggests that natural fibers, in direct contact with the skin, the body's largest organ, may transmit measurable vibrational frequencies. Such resonance could contribute to sensory, emotional, and therapeutic benefits, positioning handloom textiles as "high-vibration garments" with the potential to enhance human well-being. Although this remains an evolving field of inquiry, establishing empirical baselines opens pathways for interdisciplinary research and offers a compelling value proposition for markets increasingly conscious of wellness and sustainability.

The study attempts to conceptualize an integrated framework of oscilloscope-AI-artisan feedback system and establish its feasibility as a roadmap to enhance quality control in handloom production, thus supporting marketability and artisan livelihoods. The research employs a mixed-method approach, synthesizing experimental data from existing textile studies with qualitative insights from artisans, technologists, and designers. By bridging artisanal intelligence with scientific precision, this study repositions handlooms as climate-resilient and wellness-oriented assets within the global circular economy. It delivers both a technological framework and a philosophical vision, showing that progress in fashion emerges from harmonizing tradition with innovation. The study concludes with policy recommendations for exploratory certification frameworks on fabric resonance, integration of AI diagnostics in handloom clusters, and targeted artisan incentives. The research affirms that the future of sustainable textiles lies in data-enabled craftsmanship, where each woven thread embodies cultural heritage, measurable quality, and ecological balance.

Keywords: Handloom textiles, vibrational resonance, oscilloscope diagnostics, AI quality mapping, sustainable fashion, circular economy

Introduction

The global textile sector faces mounting environmental and social pressures. Industrial fast fashion contributes roughly 10 percent of global carbon emissions, significant wastewater pollution, and tens of millions of tonnes of waste annually. Rapid production cycles, synthetic fibers, and chemically intensive dyeing exacerbate ecological degradation and displace low-carbon artisanal practices (Aponte et al., 2024; Niinimäki et al., 2020; Fletcher, 2008).

India's handloom sector is both a heritage industry and a low-impact alternative: it produces the majority of global handwoven fabric, engages millions in livelihoods, and typically operates with lower carbon and water footprints than mechanized systems (Ministry of Textiles, 2024; Bardhan and Bhattacharya, 2022). Strengthening handlooms can therefore support rural economies and advance SDGs 8, 12, and 13. Beyond ecological and socio-economic value, handmade fabrics may possess an underexplored physical property, that is, vibrational resonance. Natural fibers (cotton, wool, and silk) register measurable responses to stress and loading (Karimah et al., 2021; Ding, Pan and Zhao, 2018), and preliminary work links textile–skin interactions to physiological responses and sensory perception (Zimniewska et al., 2002; Laing, 2019). Traditional health systems have long associated fibers and dyes with embodied effects; documenting such links with contemporary methods could connect sustainability, heritage, and wellness narratives (Wisdomlib—Caraka & Suśruta, 2021; Athira and Jishnu, 2022).

However, translating these possibilities into marketable, scalable advantages is constrained by diagnostic gaps. Variability in yarn twist, weave density, and dye uptake undermines reproducibility and buyer confidence (Chavan, 2001; Kadolph, 2007). Standard textile tests (tensile, abrasion, and colorfastness) are often destructive, costly, and impractical for low-volume artisanal contexts, leaving artisans dependent on tacit sensory assessments that resist standardization (Sankaran, Nedumpillil and Jose, 2022). This diagnostic deficit contributes to persistent undervaluation of handlooms despite their environmental strengths (Niinimäki et al., 2020).

This study asks whether oscilloscopes, instruments that record waveform signatures, can be adapted as non-destructive diagnostics for fabrics and whether interpretable AI can translate those signatures into artisan-usable feedback. Oscilloscopes capture signals sensitive to vibration, conductivity, elasticity, and dye bonding; when combined with decision-tree reasoning, these signals may be converted into simple, actionable prompts (e.g., reduce warp tension, extend soak time), reducing trial-and-error, material wastage, and rejection rates (Guo and Berglin, 2009; Metin and Bilgin, 2024; Zhang et al., 2023).

The dual rationale is (1) to position handlooms as climate-positive textiles that can scale without ecological compromise, and (2) to empirically document resonance as a differentiator that may support wellness-oriented positioning in premium markets. The study is exploratory: it synthesizes secondary experimental evidence with primary stakeholder perspectives to develop a feasibility model rather than reporting pilot trials.

Accordingly, the research pursues two objectives: (i) to document resonance-relevant properties of representative natural fibers using oscilloscope-relevant literature and (ii) to assess the conceptual feasibility of integrating AI-assisted, artisan-centered feedback into handloom-relevant workflows. By linking artisanal knowledge with measurable diagnostics, the study outlines a roadmap for enhancing quality, marketability, and livelihoods in India's handloom sector.

Literature Review

Handlooms and climate change mitigation

Handmade textiles are recognized as climate-positive alternatives to industrial production. Compared to powerlooms and synthetic-dominated systems, handlooms consume far less energy (Sengupta, 2014), use biodegradable fibers (Mehta, 2023), and employ eco-friendly dyes and biomordants with lower environmental impact (Pizzicato et al., 2023). The water footprint of handwoven cotton is substantially lower than that of polyester blends dependent on petrochemicals and energy-intensive processing (Chapagain et al., 2006; Muthu, 2014; Shen, Worrell and Patel, 2010). Operating largely without fossil-fuel machinery, rural handloom clusters represent some of the lowest-energy textile systems worldwide. Strengthening this sector can thus advance India's 2030 emission-intensity reduction targets (Government of India, 2022) while supporting climate adaptation and decentralized livelihoods (Bardhan and Bhattacharya, 2022; Fletcher, 2014).

Challenges of quality standardization

Despite ecological and social advantages, handlooms face persistent quality inconsistency. Variations in yarn twist, weave density, and dye uptake reduce reproducibility and buyer trust (Chavan, 2001). Standard tests for tensile strength, abrasion resistance, and colorfastness rely on destructive sampling (Kadolph, 2007; Namitha et al., 2022). Artisans instead rely on tacit methods of touch and visual assessment, which resist standardization (Guo and Ahn, 2023; Sankaran, Nedumpillil and Jose, 2022). The absence of portable, non-destructive diagnostic tools remains a major bottleneck for quality assurance.

Oscilloscopes in textile diagnostics

Traditionally used in electronics, oscilloscopes measure waveform signals that represent material behavior. Variations in vibration frequency correspond to elasticity, fiber density, and moisture content, while conductivity shifts reveal dye bonding and surface interaction (Guo and Berglin, 2009). These instruments provide non-invasive, real-time data that preserve fabric integrity, an essential requirement in low-waste artisanal production systems.

AI in textile quality control

Artificial intelligence is increasingly applied in industrial quality control for defect detection and process monitoring (Ozek et al., 2025). Deep learning models can identify faults such as broken ends, knots, or shade variations (Hassan et al., 2024; Li et al., 2021; Xie and Wu, 2020), but they demand extensive datasets and computational power. For decentralized craft contexts, interpretable and low-complexity models—such as decision trees—are more practical. These can map oscilloscope readings to simple actions: a vibration shift may indicate “reduce loom tension,” while conductivity drift during dyeing could suggest “extend soak time” (Guo and Berglin, 2009; Zhang et al., 2023). Such frameworks may augment artisan decision-making rather than replace it, positioning AI as a collaborative tool for skill amplification.

Resonance and wellness dimensions

An emerging dimension of handmade textiles concerns vibrational resonance and its potential link to human well-being. Fabrics display distinct frequency responses depending on fiber composition and weave structure (Blaga, Grosu and Seghedin, 2022; Ding, Pan and Zhao, 2018). Wearable-sensor and fabric-vibration research indicates that the vibration spectrum or surface frequency characteristics of textiles can influence tactile comfort and wearer perceptions (Ding, Pan and Zhao, 2018). Traditional Ayurvedic texts describe cotton as cooling, silk as balancing, and wool as warming in their energetic effects on the body (Krishnamurthy, 2018; Matthews, n.d.; Shukla, Shukla and Baghel, 2015). Establishing empirical resonance baselines for natural and azo-free dyed fabrics could therefore enable certification of "high-vibration" textiles aligned with wellness-oriented markets.

Adoption factors: infrastructure and capacity

Feasibility in rural clusters depends on affordability and accessibility. Shared access through cooperative facilities or Common Facility Centres (CFCs) can reduce diagnostic costs by 60–75 percent (Ministry of Electronics & Information Technology, 2023). NGO-led craft-tech hubs have demonstrated that local diagnostic access reduces defect rates and enhances buyer confidence. Capacity building remains essential: vernacular, peer-led training in technical skills can reduce operational errors by 20–35 percent (Ministry of Micro, Small & Medium Enterprises, 2022; United Nations Industrial Development Organization, 2013). Integrating such training into Skill India and the Textile Sector Skill Council could normalize digital diagnostics within artisanal education systems.

Global south context and knowledge transfer

India's handloom sector shares structural similarities with craft-based economies across the Global South, including African cotton guilds, Andean wool cooperatives, and Southeast Asian silk clusters. These decentralized, culturally embedded systems face similar challenges of quality assurance and competitiveness. South–South collaboration through waveform libraries, calibration datasets, and cooperative innovation hubs could accelerate diffusion of the oscilloscope–AI model (Bassi and Chopra, 2025). Such partnerships position handmade textiles as globally competitive, climate-aligned alternatives to industrial fast fashion.

Research Gap and Rationale

Three gaps motivate this research. Firstly, non-destructive diagnostics remain limited. Standard tests (tensile, abrasion, and colorfastness) require sample consumption and are impractical for artisanal, low-volume contexts. Secondly, signal-to-action translation is lacking. Although machine learning supports industrial defect detection, accessible systems that convert sensor waveforms into craft-relevant instructions are absent; decision-tree reasoning offers an interpretable pathway. Thirdly, resonance evidence is preliminary. Materials research shows measurable vibration signatures, but standardized resonance baselines across fibers and dyes are missing, limiting wellness or certification claims. Collectively, these gaps restrict the development of portable, participatory diagnostics that connect artisanal knowledge with measurable quality control. Despite rising interest in sustainable fashion, these three gaps continue to hinder the scientific and scalable validation of handloom textiles. Bridging these gaps through portable, AI-assisted, participatory diagnostics can link artisanal knowledge with scientific precision, improving quality consistency, strengthening market trust, and positioning Indian handlooms as climate-positive and wellness-aligned textiles.

Objectives

This study aims to conceptually establish the feasibility of measuring and interpreting the vibrational resonance of natural fabrics using oscilloscopes and AI-assisted methods as a pathway to improving quality diagnostics in handloom-relevant textile production. The research is exploratory in nature and does not include pilot testing; instead, it synthesizes existing experimental data with stakeholder perspectives to design an adaptable framework. Specifically, the study seeks to

- Identify and compare vibrational-resonance characteristics of representative natural fabrics (cotton, wool, and silk) from secondary literature.
- Develop a conceptual oscilloscope-AI decision-tree framework to translate diagnostic signals into predictive quality insights to assist sustainable handloom production.
- Assess stakeholder perceptions regarding feasibility, usability, and integration within craft-based production systems.

Methodology

This study employed a mixed-method approach, combining synthesis of existing experimental findings with primary qualitative data from key stakeholders working with the handloom sector. Secondary data analysis included a review of textile research that provided experimental baselines on vibration frequency, conductivity shifts under humidity, dye absorption, and elasticity. The findings from prior studies were consolidated to highlight measurable behaviors relevant to handlooms. This evidence base established the technical plausibility of using oscilloscopes in textile diagnostics.

To gain stakeholder insights, primary data was collected from 10 artisans, 4 textile technologists, and 8 sustainable fashion designers. Artisans were drawn from cotton clusters in Andhra Pradesh and Rajasthan, wool in Ladakh, and silk in Assam; dyers were drawn from Gujarat, each with 10–20 years of weaving or dyeing experience. Textile technologists, with 8–15 years of expertise in textile engineering and quality testing, provided scientific validation of fabric properties. Designers, all working with handloom-based collections for 7–12 years, offered insights on linking artisan production with sustainable fashion markets. This sample was chosen to combine practitioner, technical, and design perspectives for a holistic understanding of handmade textile scalability. Semi-structured interviews were conducted alongside two focus group discussions (one with artisans, one with designers and technologists). The primary themes revolved around challenges in quality control, feasibility of oscilloscope diagnostics, anticipated benefits (consistency, reduced wastage, buyer trust), and concerns (cost, training, cultural fit).

The data analysis entailed comparative synthesis where literature-based experimental data was cross-referenced with stakeholder inputs to propose an integrated oscilloscope–AI feasibility model. The qualitative analysis included thematic coding of interviews and FGDs, with representative quotations presented in the results section.

Conceptual Framework

The conceptual framework (Figure 1) was developed by synthesizing secondary research on textile diagnostics and AI applications with exploratory insights from focus group discussions and semi-structured interviews involving artisans, textile technologists, and designers. These inputs grounded the framework in the practical realities of handloom clusters, including loom adjustments, dyeing practices, and artisans' receptivity to feedback systems. As no pilot testing has yet been conducted, the framework remains exploratory and will be refined through systematic primary analysis and field validation in future research phases.

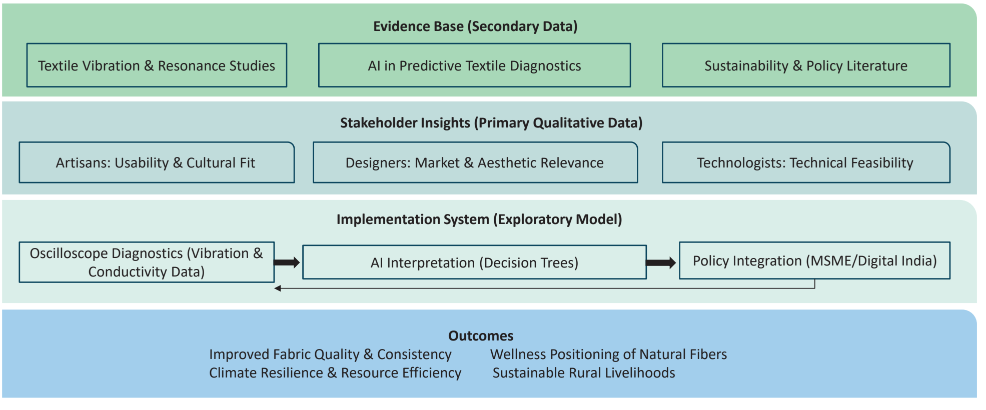


Figure 1: Integrated conceptual framework: Oscilloscope-AI-Artisan feedback system for sustainable handloom production

Results

This section synthesizes secondary data from textile material studies with oscilloscope-based diagnostics to establish measurable vibration, conductivity, and elasticity relationships among natural fibers. Together, these findings demonstrate the technical feasibility of non-destructive, AI-interpretable textile diagnostics and their relevance to handloom applications.

Vibration frequency and elastic recovery

The oscillation vibration analysis reveals distinct resonance signatures across natural fibers, shaped by their internal molecular configuration and elastic recovery behavior (Blaga, Grosu and Seghedin, 2022; Ding, Pan and Zhao, 2018). Wool, with its crimped and spring-like helical structure, demonstrates the highest vibration frequency and strong rebound capacity. Cotton exhibits moderate flexibility due to its twisted ribbon morphology, while silk, composed of smooth continuous filaments, shows lower resonance and a softer damping response (Kadolph, 2007; Morton and Hearle, 2008). Table 1 presents comparative oscillation frequencies. Wool registers the highest resonance (~32 Hz), followed by cotton (~18 Hz) and silk (~9 Hz). These distinctions validate the use of oscilloscopes as non-destructive tools for assessing tactile performance and structural stability in natural yarns. Such vibration signatures also form repeatable, quantifiable datasets suitable for AI-enabled quality prediction.

Table 1: Oscillation frequency and elastic recovery of fibres

Fabric Type	Average Oscillation Frequency (Hz)	Elastic Recovery	Resonance Behavior	Supporting Literature
Cotton	~18	Moderate	Balanced flexibility; absorbs stress evenly	Kadolph (2007); Harris, Mizell and Fourt (1942)
Wool	~32	High	Strong rebound, high tensile recovery	Kadolph (2007); Harris, Mizell and Fourt (1942)
Silk	~9	Low	Softer tension curve, prone to damping	Kadolph (2007); Harris, Mizell and Fourt (1942)

Hygroscopicity and conductivity

To examine moisture responsiveness, resistance values were compiled across relative humidity (RH) levels from established fiber studies (Morton and Hearle, 2008; Tao, 2001). Moisture absorption influences comfort, finish, and electro-physical behavior, parameters that are increasingly relevant for predictive AI-based textile grading systems. Table 2 shows that resistance decreases as humidity rises from 20 percent to 80 percent RH. Wool exhibits the steepest decline (~48 percent), reflecting its high moisture regain capacity. Cotton displays a moderate reduction (~25 percent), while silk shows minimal change (~7 percent) due to its dense filament structure and lower porosity. These results align with known hygroscopic profiles and help model fiber behavior under variable climatic conditions.

Table 2: Electrical resistance across humidity Levels

Fabric Type	Resistance at 20 % RH (Ω)	Resistance at 50 % RH (Ω)	Resistance at 80 % RH (Ω)	Avg. Change (%)	Supporting Literature
Cotton	200	180	150	25 % ↓	Morton and Hearle (2008); Tao (2001)
Wool	250	190	130	48 % ↓	Morton and Hearle (2008)
Silk	300	290	280	7 % ↓	Morton and Hearle (2008)

Conductivity shift after dyeing

Dye–fiber interactions influence surface conductivity by altering ionic pathways and moisture-binding characteristics. Post-dye oscillation vibration readings from secondary textile studies consistently show reduced electrical resistance in cotton and wool dyed with natural or azo-free dyes (Morton and Hearle, 2008; Shenai, 1996; Samanta and Agarwal, 2009). This reduction reflects stronger dye–fiber bonding and improved ionic conductivity. Table 3 consolidates pre- and post-dye values. Cotton shows a 12–14 percent decline in resistance, wool 15–17 percent, and silk only 2–4 percent, correlating with differences in moisture regain and filament density. These conductivity shifts provide quantifiable parameters that AI systems can use to evaluate dye uniformity, finishing quality, and fiber responsiveness.

Table 3: Consolidated pre- and post-dye conductivity values

Fabric	Pre-Dye Resistance (Ω)	Post-Dye Resistance (Ω)	Change (%)	Supporting Literature
Cotton	180	160	11%	Shenai, 1996; Samanta and Agarwal, 2009
Cotton	180	155	14%	Samanta and Agarwal, 2009

Wool	200	170	15%	Shenai, 1996; Samanta and Agarwal, 2009
Wool	200	165	17%	Samanta and Agarwal, 2009
Silk	290	285	1.7%	Morton and Hearle, 2008; Shenai, 1996
Silk	290	280	3.4%	Samanta and Agarwal, 2009

Elasticity and fibre density

Elasticity and fiber density jointly influence how fibers respond to tensile load, recover from deformation, and contribute to drape and performance. Wool demonstrates the highest elasticity due to its three-dimensional crimped structure and relatively lower density, findings consistently supported in textile science literature (Kadolph, 2007; Morton and Hearle, 2008). These properties place wool in the "high-performance" mechanical category. Cotton, being denser and more compact, exhibits moderate elasticity linked to its twisted ribbon morphology (Gupta, 2014; Kadolph, 2007). Its structural features allow balanced performance but reduced rebound relative to wool. Silk, with its smooth continuous filament and soft damping behavior, offers superior drape but lower elasticity and rebound, positioning it in the soft-damping performance spectrum (Gupta, 2014; Morton and Hearle, 2008). This mechanical profile provides essential complementary context to oscilloscope-derived vibration patterns.

Synthesis of resonance, conductivity, and elasticity

The combined analysis of vibration frequency, humidity-driven conductivity, dye-related electrical shifts, and fiber elasticity–density relationships provides a coherent performance profile for natural yarns. Cotton (~18 Hz), wool (~32 Hz), and silk (~9 Hz) display distinct resonance behaviors that correspond to differences in stiffness, moisture responsiveness, and mechanical recovery (Kadolph, 2007; Morton and Hearle, 2008). These integrated parameters confirm the effectiveness of oscilloscope-based methods for non-destructive yarn evaluation. Coupled with AI, such multidimensional datasets can enable predictive quality grading, defect detection, and enhanced process optimization across handloom production.

Integrated stakeholder insights and feasibility analysis

This section synthesizes insights from focus group discussions, semi-structured interviews, and surveys with artisans, technologists, and designers to assess the feasibility of integrating oscilloscope–AI diagnostics in handloom clusters. Building on resonance-based findings, it examines how yarn-level vibration precision translates into fabric behavior through loom tension and weaving technique. Although no pilot testing has yet been conducted, qualitative evidence indicates strong conceptual, cultural, and ethical readiness for adoption.

Technical and functional feasibility

Participants across all stakeholder groups acknowledged that vibration-based diagnostics could improve fabric consistency, reduce rework, and enhance efficiency. A weaver from Rajasthan observed, “If the loom could show when the tension needs to reduce, we could avoid broken yarns and lost hours.” Such statements illustrate how artisans link vibration feedback to practical problem-solving, aligning with established findings that early-stage diagnostics enhance reproducibility and material optimization (Kadolph, 2007; Saville, 1999). Technologists affirmed technical feasibility, noting that each raw material and weaving method “has its own vibration signature,” directly reflecting resonance principles (Guo and Berglin, 2009). They recommended developing a fabric frequency library to enable comparative AI analysis across fibers, laying the groundwork for predictive quality analytics. Designers emphasized commercial relevance. As one stated, “Predictive data on color or texture could help assure consistency before export, not after rejection. This reinforces Niinimäki’s (2018) argument that transparency and certification strengthen market confidence in sustainable fashion. Collectively, these insights confirm high conceptual readiness and position oscilloscope–AI tools as assistive, not replacement, technologies—bridging artisanal intuition with measurable precision.

Cultural alignment and ethical design

Stakeholders stressed that technology must adapt to cultural rhythms and uphold craft-based epistemologies. A silk artisan from Assam remarked, “We do not start dyeing on certain days; if technology can wait for us, it respects our way of working.” Similarly, a wool weaver from Ladakh added, “Our work changes with the season—tools should too.” These reflections exemplify participatory research principles (Chambers, 1994; Mansuri and Rao, 2013), underscoring that adoption must harmonize with traditional cycles and embodied practices.

Ease of use emerged as a universal condition. Artisans preferred visual dashboards using familiar cues such as terms like “yarn stretch” or “loom balance,” rather than numerical data. Designers suggested color-coded feedback mechanisms tied to tactile and vibration sensors. This kind of participatory co-design aligns with craft-based co-creation models in textile clusters where interface design draws directly on artisan vocabularies and practices (Narasimhan and Mahajan, 2023).

Ethical concerns included non-destructive testing and fair compensation during field trials, echoing reciprocity and mutual-benefit norms central to participatory research (Nueces et al., 2012; Marrone, Nieman and Coco, 2022). Technologists associated the vibrational behaviour of natural fibres with tactile comfort, while designers described high-resonance textiles as “living fabrics” that communicate warmth and calm, an observation consistent with Blaga, Grosu and Seghedin (2022), who links fibre resonance to sensory well-being.

Together, these perspectives affirm that ethical co-design anchored in cultural pace, sensory awareness, and shared value forms the foundation for feasible and inclusive innovation in the handloom ecosystem.

The integrated feasibility model

Synthesizing stakeholder insights with secondary research, the Integrated Feasibility Model outlines a seven-step pathway for adopting oscilloscope–AI diagnostics in handloom clusters (Figure 2). It integrates technical accuracy, socio-cultural alignment, and policy frameworks to ensure that scientific precision coexists with human-centered design. Table 4 describes the seven-step pathway of the feasibility model, based on primary and secondary data analysis.

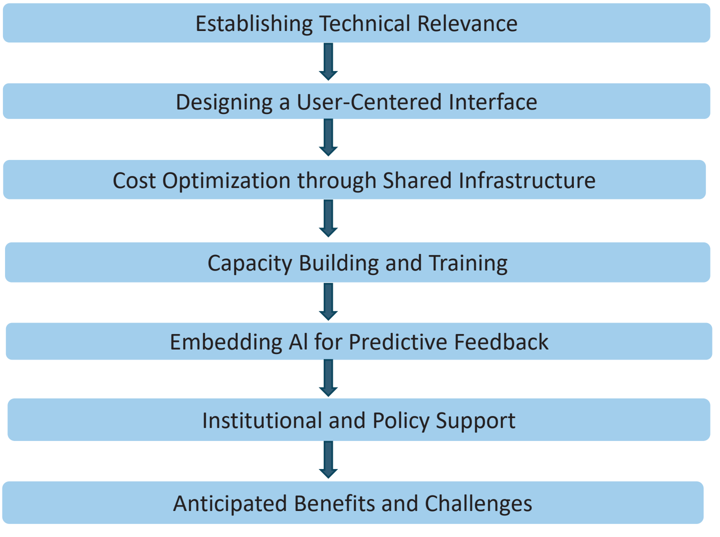


Figure 2: Feasibility model for oscilloscope–AI integration in handloom clusters

Table 4: Seven-step pathway of the feasibility model

Step	Focus Area	Key Insights
1.	Technical Relevance	Oscilloscopes can non-invasively capture vibration and conductivity shifts. Technologists confirmed feasibility; validated by Guo and Berglin (2009).
2.	User-Centered Interface	Dashboards must use craft-relevant visuals and analogies. Supported by artisans' feedback and participatory co-design literature (Hu, Hur and Thomas, 2023).
3.	Cost Optimization	Shared infrastructure via cooperatives and CFCs reduces input and operating costs, consistent with MSME cluster policies (Bisht, 2016; Ministry of Micro, Small & Medium Enterprises, 2022; Buteau, 2021).
4.	Capacity Building	Phased, vernacular, peer-led training builds confidence and reduces user error (Rogers, 2003). repeatedly highlighted by respondents.
5.	Predictive Feedback	AI interpretation of vibration data could pre-empt weaving or dyeing defects (Bhuiyan et al., 2022). Stakeholders identified this as the most valuable feature.
6.	Institutional Integration	Policy alignment with Digital India, MSME Cluster Development, and sustainable textile missions ensures systemic adoption (Bardhan and Bhattacharya, 2022; Ministry of Electronics & Information Technology, 2023).
7.	Expected Outcomes	Enhanced quality, reduced wastage, stable incomes, and validated authenticity (Kadolph, 2007; World Trade Organization, 2016).

Interpretive summary

Stakeholder insights and secondary data converge on a shared understanding: artisans perceive resonance as the "harmony of threads," while scientists interpret it through measurable vibration frequencies. This synthesis bridges intuition and empirical precision, positioning resonance as a shared language between craft and science. The findings affirm that artisans, designers, and technologists regard technology as a partner, enhancing rather than replacing skill. By embedding oscilloscope–AI diagnostics within participatory, ethical, and policy-aligned systems, the feasibility model redefines modernization as continuity, where traditional intelligence and digital analytics together shape a sustainable, resonance-based future for India's handloom sector.

Discussion and Policy Implications

This study bridges textile diagnostics, artificial intelligence, and sustainable handloom production by developing a feasibility-based framework for integrating oscilloscope–AI diagnostics within artisanal systems. The findings demonstrate that combining scientific precision with craft-based intuition can enhance product quality, environmental sustainability, and rural livelihoods.

Integrating scientific diagnostics with craft knowledge

The integrated feasibility model and stakeholder insights reveal that successful adoption depends on aligning technological innovation with artisanal epistemology. Artisans' experiential understanding of "resonance" parallels scientific concepts of mass, stiffness, and damping, confirming that diagnostic tools can complement rather than replace tacit craft intelligence. This synergy embodies the inclusive innovation paradigm, where modern instruments reinforce traditional systems (Chambers, 1994; Mansuri and Rao, 2013). Stakeholders expressed readiness for vibration-based feedback, describing weaving in rhythmic terms, "When the loom hums evenly, the cloth feels alive." Such metaphors signal compatibility between artisanal perception and diagnostic interpretation. The model thus represents a hybrid framework, technologically advanced yet culturally grounded, that is capable of preserving authenticity while enabling measurable precision.

Advancing policy alignment and institutional integration

India's Digital India and MSME Cluster Development programs (Ministry of Electronics & Information Technology, 2023) provide a practical route to implement the model in craft clusters via common facility centers. The oscilloscope–AI systems can be integrated within MSME and Handloom Schemes under "Smart Cluster" initiatives. Developing vibration databases can standardize diagnostics and create scientific certification layers for handloom textiles, enhancing authenticity and export credibility (World Trade Organization, 2016). Diagnostic certification can be used to access green finance and sustainable trade platforms. Further artisan-centric data infrastructure can be built by creating an open Handloom Data Commons, ensuring data sovereignty and fair benefit-sharing. There is also scope to set up digital craft labs through design-technology partnerships. Integration with traceability platforms strengthens participation in sustainable value chains, supporting SDG 8 (Decent Work), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action). By reducing waste, improving dye consistency, and extending fiber life, the model enhances both environmental and economic resilience in rural clusters.

Addressing implementation challenges

Despite conceptual readiness, several constraints must be addressed:

- Algorithmic calibration: AI models require diverse training across yarns, dyes, and weaving styles.
- Environmental variability: Portable oscilloscopes must be ruggedized for temperature and humidity shifts.
- Digital literacy: Training should be iterative, visual, and context-specific.
- Ethical oversight: Transparent, human-supervised AI interpretation is vital to avoid misjudgment.

These reinforce that diffusion of technology in heritage sectors must maintain both precision and participation, ensuring innovation strengthens dignity and agency.

Contributions of the Study

This research contributes across three interconnected domains: technical innovation, socio-cultural empowerment, and policy-market integration, reframing handlooms as instruments of sustainable and wellness-aligned fashion.

Technical innovation: oscilloscope diagnostics in handmade textiles

The study pioneers adapting oscilloscopes, traditionally electronic instruments, to capture real-time data on vibration, conductivity, dye uptake, and elasticity in handmade fabrics. Integrating interpretable AI decision-tree models transforms diagnostics from descriptive to predictive, enabling artisans to make precise, real-time adjustments during weaving and dyeing.

Socio-cultural empowerment: participatory and ethical technology design

Innovation in craft sectors must align with cultural rhythms and lived knowledge systems. Through participatory co-design, non-destructive testing, and reciprocity safeguards, the framework preserves artisan agency and ethical inclusion, contrasting earlier mechanization that disrupted community structures (Scrase, 2003; Venkatesan, 2009).

Policy and market relevance: the sustainability-wellness nexus

By linking measurable vibrational resonance with wellness and sustainability (Blaga, Grosu and Seghedin, 2022; Global Wellness Institute, 2023), handmade textiles can evolve from heritage crafts to premium, climate-positive products. The model aligns with national digital and MSME initiatives, offering a scalable route toward certification and global market positioning.

Limitations of the Study

Despite its novelty, several limitations remain:

- Experimental validation: The study draws on secondary and qualitative data but lacks multi-site quantitative testing across fiber types and environments.
- Resonance–wellness correlation: The link between vibration frequencies and well-being remains theoretical, requiring interdisciplinary biomedical validation.
- AI scope: Decision-tree models, though interpretable, limit generalization; larger waveform datasets and hybrid algorithms are required.
- Infrastructure: Limited electricity, internet access, and funding in rural clusters may constrain equitable adoption without targeted policy support.

Future Research Priorities

Building on current findings, future research should validate and expand the Integrated Feasibility Model through empirical field pilots and interdisciplinary study. Four priority directions are identified:

- Cluster-based pilot validation: Conduct field trials across cotton (Gujarat), silk (Assam), and wool (Himachal Pradesh) clusters to test diagnostic precision, vibration–yardage correlations, defect prediction accuracy, and productivity outcomes.
- Biomedical and psychophysical studies: Collaborate with health scientists to examine whether fiber resonance influences wearer comfort, thermal experience, or psychophysiological well-being, linking material frequencies with sensory or mood responses.
- AI fabric frequency libraries: Develop open-source fabric waveform libraries that map vibration signatures to yarn types, weave structures, and quality variations. These datasets can train hybrid AI models capable of real-time grading and defect detection.
- Socio-economic and market impact evaluation: Undertake longitudinal studies to assess income stability, gender equity, labor dignity, and skill transmission among artisans, while exploring market positioning strategies that frame handmade textiles as wellness-oriented and climate-positive products.

Conclusion

This study demonstrates the scope of integrating oscilloscope diagnostics with AI-driven interpretation to transform handloom production from tacit intuition into a system of predictive, reproducible quality control. By measuring parameters such as vibration, conductivity, dye uptake, and elasticity non-destructively, oscilloscopes can assist in democratizing diagnostic precision once confined to industrial laboratories. Through interpretable AI decision-tree models, these readings can be translated into real-time feedback, helping artisans reduce defects, minimize material waste, and strengthen buyer confidence in handmade textiles. Findings from secondary analyses indicate that natural fabrics exhibit distinct vibrational signatures, suggesting a potential link between fiber resonance, sensory well-being, and wearer comfort. Though preliminary, this connection introduces a promising research frontier, positioning Indian handlooms not only as climate-positive but also as wellness-oriented textiles within global sustainability frameworks.

The study further confirms that ethically designed technology can enhance rather than erode traditional craftsmanship. Participatory co-design, non-destructive testing, and shared infrastructure ensure artisans remain co-creators in the digital evolution of craft, preserving cultural authenticity while advancing technical precision and scalability. While challenges remain, such as validating resonance–wellness correlations, refining AI calibration, and conducting large-scale field pilots, the proposed framework provides a robust foundation for interdisciplinary innovation. Embedding oscilloscope–AI diagnostics within handloom clusters can improve productivity, stabilize incomes, and enable traceable, globally recognized quality standards, positioning Indian handlooms as climate-positive and wellness-driven textiles within the circular economy. Future integration of these diagnostics can redefine sustainable fashion as a convergence of heritage, precision, and human well-being.

References

Aponte, N.O., Gómez, J.H., Argüelles, V.T., and Smith, E.D., 2024. Fast fashion consumption and its environmental impact: a literature review. *Sustainability: Science, Practice and Policy*, [e-journal] 20(1). https://doi.org/10.1080/15487733.2024.2381871.

Athira, V.P. and Jishnu, R., 2022. Concept of vastra dharana in brhattrayis and in charucharya. *International Ayurvedic Medical Journal (IAMJ)*. [pdf] Available at: <https://www.wisdomlib.org/uploads/journals/iamj/2022-issue-09-september/2503_2508.pdf> [Accessed 10 October 2025].

Bardhan, A. and Bhattacharya, A., 2022. Role of traditional crafts in sustainable development and building community resilience: case stories from India. *Culture, Society, Economy, Politics*, 2(1), pp.38–50.

Bassi, I. and Chopra, K., 2025. *The climate intelligent organization: build a prosperous and resilient future for the planet through AI-powered climate intelligence*. Hoboken: John Wiley & Sons.

Bhuiyan, M.H.R., Arafat, I.M., Rahaman, M., Toha, T.R., Alam, S.M.M., 2022. *Devising a vibration-based fault detection system for textile machinery.* In: Longfei, S., Bodhi, P. (eds) Mobile and Ubiquitous Systems: Computing, Networking and Services. MobiQuitous 2022. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, 492. Springer, Cham. https://doi.org/10.1007/978-3-031-34776-4_1.

Bisht, S.**,** 2016. *Use of Information and Communication Technologies (ICT) among artisan organisations in India: Survey Report*. UNESCO New Delhi in collaboration with AIACA & GoCoop. [pdf] Available at: <https://www.aiacaonline.org/wp-content/uploads/2018/06/UNESCO-ICT-Report-Final_2016.pdf> [Accessed 10 November 2025].

Blaga, M., Groşu, C. and Seghedin, N. E., 2022. Measuring the natural frequencies of knitted materials for protection against vibration. *Industria Textilă*, 73(1), pp.13–19.

Buteau, S., 2021. Roadmap for digital technology to foster India's MSME ecosystem—opportunities and challenges. *CSIT*, 9, pp.233–244. https://doi.org/10.1007/s40012-021-00345-4.

Chambers, R., 1994. The origins and practice of participatory rural appraisal. *World Development*, [e-journal] 22(7), pp.953–969. https://doi.org/10.1016/0305-750X(94)90141-4.

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G. and Gautam, R., 2006. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. *Ecological Economics*, [e-journal] 60(1), pp.186–203. https://doi.org/10.1016/j.ecolecon.2005.11.027.

Chavan, R.B., 2001. Environment-friendly dyeing processes for cotton. *Indian Journal of Fibre & Textile Research*, 26(1–2), pp.93–100.

Ding, S., Pan, Y. and Zhao, X., 2018. Humanoid identification of fabric material properties by vibration spectrum analysis. *Sensors,* [e-journal] 18(6), 1820. https://doi.org/10.3390/s18061820.

Fletcher, K., 2008. *Sustainable Fashion and Textiles: Design Journeys*. London: Earthscan.

Fletcher, K., 2014. *Sustainable Fashion and Textiles: Design Journeys.* 2nd ed. Abingdon, Oxon: Routledge.

Global Wellness Institute, 2023. *The Global Wellness Economy: 2023*. [online] Available at: <https://globalwellnessinstitute.org/wp-content/uploads/2023/11/GWI-WE-Monitor-2023_FINAL.pdf> [Accessed 30 September 2025].

Government of India, 2022. *India's updated first nationally determined contribution under the Paris agreement (2021-2030)*. [online] Available at: <https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf> [Accessed 29 September 2025].

Guo, J. and Ahn, B., 2023. Tacit knowledge sharing for enhancing the sustainability of intangible cultural heritage (ICH) crafts: a perspective from artisans and academics under craft–design collaboration. *Sustainability*, [e-journal] 15(20), 14955. https://doi.org/10.3390/su152014955.

Guo, L. and Berglin, L., 2009. Test and evaluation of textile-based stretch sensors. *Proceedings of AUTEX 2009 World Textile Conference*, İzmir, Turkey, 26–28 May.

Gupta, V.B., 2014. *Structure and properties of cotton fibres*. In Handbook of Natural Fibres: Types, Properties and Factors Affecting Breeding and Cultivation. Cambridge: Woodhead Publishing.

Harris, M., Mizell, L.R. and Fourt, L., 1942. Elasticity of wool as related to its chemical structure. *Journal of Research of the National Bureau of Standards*, 29(1), pp.73–88.

Hassan, S.A., Beliatis, M.J., Radziwon, A., Menciassi, A. and Oddo, C.M., 2024. Textile fabric defect detection using enhanced deep convolutional neural network with safe human–robot collaborative interaction. *Electronics*, [e-journal] 13(21), 4314. https://doi.org/10.3390/electronics13214314.

Hu, J., Hur, E. and Thomas, B., 2023. Value-creating practices and barriers for collaboration between designers and artisans: a systematic literature review. *International Journal of Fashion Design, Technology and Education*, [e-journal] 17(1), pp.25–36. https://doi.org/10.1080/17543266.2023.2228337.

Kadolph, S.J., 2007. *Textiles.* 10th ed. Upper Saddle River, NJ: Pearson/Prentice Hall.

Karimah, A., Ridho, M.R., Munawar, S.S., Adi, D.S., Ismadi, Damayanti, R., Subiyanto, B., Fatriasari, W. andFudholi, A., 2021. A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations. *Journal of Materials Research and Technology*, [e-journal] 13, pp.2442-2458. https://doi.org/10.1016/j.jmrt.2021.06.014.

Krishnamurthy, M.S., 2018. Impact of cloth colour and material on body and mind. *Easy Ayurveda*. [online] Available at: <https://www.easyayurveda.com/2018/09/25/clothing-colour-material/ > [Accessed 27 November 2025].

Laing, R.M., 2019. Natural fibres in next-to-skin textiles: current perspectives on human body odour. *SN Applied Sciences*, [e-journal] 1, 1329. https://doi.org/10.1007/s42452-019-1388-1.

Li, C., Li, J., Li, Y., He, L., Fu, X. and Chen, J., 2021. Fabric defect detection in textile manufacturing: a survey of the state of the art. *Security and Communication Networks*, [e-journal] https://doi.org/10.1155/2021/9948808.

Mansuri, G. and Rao, V., 2013. *Localizing development: does participation work?* Washington, DC: World Bank.

Marrone, N. L., Nieman, C. L. and Coco, L., 2022. Community-based participatory research and human-centered design principles to advance hearing health equity. *Ear and Hearing*, 43(1), pp.33S–44S.

Matthews, S., n.d. Ritucharya – seasonal routines of health in ayurveda. *Yoga Therapy Institute*. [online] Available at: <https://yogatherapyinstitute.com.au/articles/ritucharya-seasonal-routines-of-health-in-ayurveda-by-dr-shaun-matthews/> [Accessed 27 November 2025].

Mehta, S., 2023. Biodegradable textile polymers: a review of current scenario and future opportunities. *Environmental Technology Reviews,* [e-journal] 12(1), pp. 441-457. doi:10.1080/21622515.2023.2227391.

Metin, A. and Bilgin, T.T., 2024. Automated machine learning for fabric quality prediction: a comparative analysis. *Peer J Computer Science*, [e-journal] 10. https://doi.org/10.7717/peerj-cs.2188.

Ministry of Electronics & Information Technology, 2023. *Annual Report 2022–23*: *English.* New Delhi: Government of India. [pdf] Available at: <https://www.meity.gov.in/static/uploads/2024/02/AR_2022-23_English_24-04-23-1.pdf> [Accessed 30 September 2025].

Ministry of Micro, Small & Medium Enterprises, 2022. *MSME Cluster Development Programme Guidelines.* [online] Available at: <https://www.dcmsme.gov.in/schemes/New-Guidelines.pdf> [Accessed 22 November 2025].

Ministry of Textiles. 2024. *Sustainability in the handloom traditions of India.* Development Commissioner (Handlooms), Government of India. [pdf] Available at: <https://handlooms.nic.in/assets/img/EBOOK/Sustainability%20in%20the%20Handloom%20Traditions%20of%20India.pdf> [Accessed 15 October 2025].

Morton, W.E. and Hearle, J.W.S., 2008. *Physical properties of textile fibres.* 4th ed. Cambridge: Woodhead Publishing.

Muthu, S.S., 2014. *Assessing the environmental impact of textiles and the clothing supply chain*. Woodhead Publishing.

Namitha, N.N., Sankaran, A., Jose, S., George, S. and Thomas, S., 2022. Destructive analytical techniques for the analysis of historic textiles. In: *Handbook of Museum Textiles*, pp.215–234. Wiley.

Narasimhan, U. and Mahajan, S., 2023. Textiles crafts and co-creation as a strategy for sustainable design pedagogy. *NIFT Journal of Fashion*, 2, pp.145–162.

Niinimäki, K., 2018. *Sustainable fashion in a circular economy*. Helsinki: Aalto University.

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T. and Gwilt, A., 2020. The environmental price of fast fashion. *Nature Reviews Earth & Environment*, [e-journal] 1, pp.189–200. https://doi.org/10.1038/s43017-020-0039-9.

Nueces, D.D.L, Hacker, K., DiGirolamo, A. and Hicks, L.S., 2012. A systematic review of community-based participatory research to enhance clinical trials in racial and ethnic minority groups. *Health Services Research*, 47(3 Pt 2), pp.1363–1386.

Ozek, A., Seckin, M., Demircioglu, P. and Bogrekci, I., 2025. Artificial intelligence driving innovation in textile defect detection. *Textiles*, [e-journal] 5(2), 12. https://doi.org/10.3390/textiles5020012.

Pizzicato, B., Pacifico, S., Cayuela, D., Mijas, G. and Riba-Moliner, M., 2023. *Advancements in sustainable natural dyes for textile applications: A review. Molecules*, [e-journal] 28(16), 5954. https://doi.org/10.3390/molecules28165954.

Rogers, E.M., 2003. *Diffusion of innovations.* 5th ed. New York: Free Press.

Samanta, A.K. and Agarwal, P., 2009. *Application of natural dyes on textiles*. New Delhi: Springer.

Sankaran, A., Nedumpillil, N.N. and Jose, S., 2022. *NDT of historic textiles — brief on theory and applications*, In: Handbook of Museum Textiles. Chichester: John Wiley & Sons.

Saville, B.P., 1999. *Physical testing of textiles*. Cambridge: Woodhead Publishing.

Sengupta, S., 2014. *Handloom clusters in India: an evaluation.* NCAER Working Paper.

Scrase, T., 2003. Precarious production: globalisation and artisan labour in the third world. *Third World Quarterly*, [e-journal] 24(3), pp.449–461. https://doi.org/10.1080/0143659032000084401.

Shen, L., Worrell, E. and Patel, M.K., 2010. Environmental impact assessment of man-made fibres. *Resources, Conservation and Recycling*, [e-journal] 55(2), pp.260–274. https://doi.org/10.1016/j.resconrec.2010.10.001.

Shenai, V.A., 1996.*Technology of Textile Processing: Vol. 3*. Bombay: Sevak Publications.

Shukla, A., Shukla, A. and Baghel, A.S., 2015. Dress and clothing: an ayurvedic perspective. *Journal of AYUSH: Ayurveda, Yoga, Unani, Siddha and Homeopathy,* [online] 4(2). Available at: <https://medicaljournals.stmjournals.in/index.php/JoAYUSH/article/view/3481> [Accessed 10 November 2025].

Tao, X., 2001. *Smart fibres, fabrics and clothing: fundamentals and applications*. Cambridge: Woodhead Publishing.

United Nations Industrial Development Organization, 2013. *Independent terminal evaluation: consolidated project for SME development in India through establishment of mutual credit guarantee schemes, cluster twinning and foreign investment and technology promotion*. UNIDO Evaluation Group. [online] Available at: <https://www.unido.org/sites/default/files/2014-01/India_SME_CT_final_0.pdf> [Accessed 12 October 2025].

Venkatesan, S., 2009. Rethinking agency: persons and things in the heterotopia of "traditional Indian craft". *Journal of the Royal Anthropological Institute*, [e-journal] 15(1), pp.78–95.

Wisdomlib, 2021. Dress and clothing — references in Caraka Saṃhitā and SuśrutaSaṃhitā. *History of Indian Medicine and Ayurveda*, Chapter 3.

World Trade Organization, 2016. *World trade report 2016: levelling the trading field for SMEs*. Geneva: World Trade Organization.

Xie, H. and Wu, Z., 2020. a robust fabric defect detection method based on improved refinedet. *Sensors*, [e-journal] 20(15), 4260. https://doi.org/10.3390/s20154260.

Zhang, J., Cosma, G., Bugby, S. and Watkins, J., 2023. Forestmonkey: toolkit for reasoning with AI-based defect detection and classification models. *IEEE Symposium Series on Computational Intelligence (SSCI),* Mexico, 5-8 December 2023.

Zimniewska, M., Huber, J., Krucińska, I., Torlińska, T. and Kozłowski, R., 2002. The influence of clothes made from natural and synthetic fibers on motor unit activity in forearm muscles. *Fibres & Textiles in Eastern Europe*, 10(4), pp.55–59.

About the author

Deepa Parameswaran, founder of Dana Prath Lifestyle Private Limited, is a sustainability advocate blending academic expertise with grassroots experience. With a Master's in Public Policy and Sustainable Development, a background in economics and fashion technology, she spent years working closely with artisans, deepening her understanding of inequality reduction, circularity, and climate-positive craft economies. Her flagship brand, Leya, partners with craft communities to create draped garments using natural yarns, azo-free dyes, and waste-minimizing techniques, while sister brand Zlay extends this mission to price-sensitive markets and supports rural economic upliftment. Deepa, a COP-27 nominee, has collaborated with UN Women and was a global policy finalist (2022). Her publication "Climate Finance for Sustainable Fashion in India" in IJSR (2024) later won the best paper award at ICTR (2025). A recipient of the Women Achiever Award (FDDI) under the Ministry of Commerce and Industry, Deepa has also been named among OutStory India's 50 Influential Leaders creating meaningful impact.

deepa.parameswaran@terisas.ac.in

Building a Conceptual Framework to Study Factors Influencing E-commerce Adoption by Handloom Weavers

Shubhangi Yadav and Binay Bhusan Jena

Abstract

The handloom sector in India holds economic importance owing to its lower capital investment needs, substantial value-addition ratio, eco-friendliness, capability to employ women and marginalized communities, and considerable potential for export and foreign exchange revenue. However, in actuality, the handloom weavers receive considerably low compensation and appreciation for the exceptional craftsmanship, leading to the decline of the handloom sector and discouraging subsequent generations from pursuing this profession. Adopting e-commerce can expand the market reach of handloom weavers, appropriately valuing their craftsmanship, thus improving their economic status and increasing employment in this sector.

This study employs the foundation of the Unified Theory of Acceptance and Use of Technology (UTAUT) model to investigate the many drivers and barriers affecting e-commerce adoption among handloom weavers. UTAUT incorporates social and psychological elements, enhancing its predictive and explanatory power; hence, it helps in examining factors that influence e-commerce adoption among handloom weavers. The preliminary qualitative investigation aimed to develop a framework that would offer essential insights for the economic advancement of handloom weavers. The research participants involved in the research work were questioned about their perceptions regarding the adoption of e-commerce. The analysis of the qualitative interviews revealed nine factors that play an influential role in the adoption of e-commerce, namely effort expectancy, social influence, performance expectancy, children›s support, relative advantage, institutional support, behavioral beliefs, and perceived risk. The nine variables may exert either a positive or negative influence on the “Actual Adoption” of e-commerce by handloom weavers. The adoption will impact the “Business Performance” of handloom weavers in two ways: market performance and financial performance. Thus, a correlation is established between the constructs of the UTAUT theory and the business performance of handloom weavers through the actual adoption of e-commerce. The research concludes with recommendations for policymakers and industry stakeholders, highlighting the need for digital literacy programs, conducive infrastructural arrangements, development of weaver-centric digital solutions, and operational assistance to support e-commerce adoption among weavers.

Keywords: E-commerce, technology adoption, handloom weavers, UTAUT, qualitative study

Introduction

The Indian handloom showcases the rich cultural heritage, artistic skill, and ingenuity of the craftsmen who intricately weave designs onto a blank canvas. In terms of creativity and modernity, the Indian handloom has seen a great change, but it is still one of the most unorganized sectors after agriculture and is crucial to rural and semi-rural communities' way of life. There are several states in the nation where handloom weaving is practiced, albeit it is declining significantly in some of them. The weavers are abandoning the sector en masse due to lack of equal opportunity.

The handloom sector is a gold mine that can significantly contribute to making "Skill India" and "Make in India" efforts successful (Ghosh, 2016). This sector has the potential to grow owing to its inherent sustainability and eco-friendly attributes. Furthermore, there is growing awareness of handloom products among both domestic and international consumers. Thus, researchers have identified that adaptation of e-commerce can resolve many problems associated with this sector (Mishra and Mohapatra, 2019). An e-commerce platform can act as a 'technology-enabled marketing-intermediation platform,' which can enable weavers to gain access to a larger market through a more efficient supply chain.

However, the literature review indicates that substantial research is necessary for the technological dimension of the handloom sector (Mishra and Mohapatra, 2019; Sarkar, 2016). It is essential to identify drivers and barriers that affect e-commerce adoption (non-adoption) among handloom weavers. This finding can significantly impact the improvement of livelihoods for a large segment of society, as the handloom sector contributes to both direct and indirect employment for 35.22 lakh weavers and allied workers (Ministry of Textiles, 2022). Therefore, this research aims to develop a theoretical conceptual model that examines the factors influencing e-commerce adoption among handloom weavers.

Literature Review

Indian handloom denotes a diverse cultural ethos ranging from exquisite fabrics, which take months to weave, to popular items of mass production for daily use. The key strengths linked with this sector include cheap labor, less capital investment, local resources, and unique craftsmanship, in addition to high appreciation and preferences by urban and international customers (Mishra and Mohapatra, 2019). However, with changing market demands, globalization, and industrialization, the handloom sector is plagued with concerns like stiff competition from power looms, less innovation, and product diversification (Hada and Chaturvedi, 2018; Misra, 2019). The Indian handloom sector is an individual-centric, weaver-driven activity; thus, it is very fragmented and usually a small-scale undertaking. Being a traditional sector, the skill of weaving is passed down from generations, so there is no formal education, and therefore they are not introduced to modern technology and infrastructure (Sabarinathan and Velamuri, 2020). The challenges of the traditional supply chain translate into less profit for the handloom weaver, leading to financial crises, the inability to buy good-quality raw materials (Misra, 2019), and the younger generation being reluctant to adopt weaving as a profession (Hada and Chaturvedi, 2018). Handloom products are also mostly available in government-organized fairs and local markets, thereby reducing the frequency of purchase by urban buyers (Majestic Mrss, 2016).

Varaganti (2017) states that the handloom sector has huge potential in terms of revenues and employment, and it is highly environmentally friendly, with one of the lowest carbon footprints. Likewise, the demand and appreciation of Indian handloom products in the global market calls for looking at various channels to reach a wide audience. In recent times, the internet has transformed businesses, rendering e-commerce an essential requirement for all the industries. Despite its infancy, the e-commerce market in India is the fastest-growing in the world. With a population of more than 1.4 billion and a fast-growing economy, the number of online shoppers is predicted to increase to 427 million by 2027. Consequently, the booming e-commerce industry is estimated to be worth over 300 billion U.S. dollars by 2030 (Minhas, 2024). Several research studies propose e-commerce adoption (Mandal, 2015) and use of social media (Humbe, 2014) for the benefit of the handloom weavers and to educate the masses about the handloom sector. The adoption of smarter marketing channels, like e-commerce, can help the weavers to reach geographically distant customers, enhance the brand value of handloom, increase sales, and thus improve their lifestyles (Venkatesh and Kumarswamy, 2016).

Therefore, it is essential to evaluate the readiness and receptiveness of handloom weavers towards the adoption of new technologies, as individuals accept or reject technology based on several criteria. Technology adoption means the acceptance, integration, and embracing of new technology. Technology acceptance, the initial phase of technology adoption, constitutes an attitude towards technology and is shaped by numerous factors (Granic, 2023). The adoption of new technologies by users can be analyzed using many established theoretical frameworks. This research utilizes the theoretical underpinning of the Unified Theory of Acceptance and Use of Technology (UTAUT) framework (Figure 1) developed by Venkatesh et al. (2003).

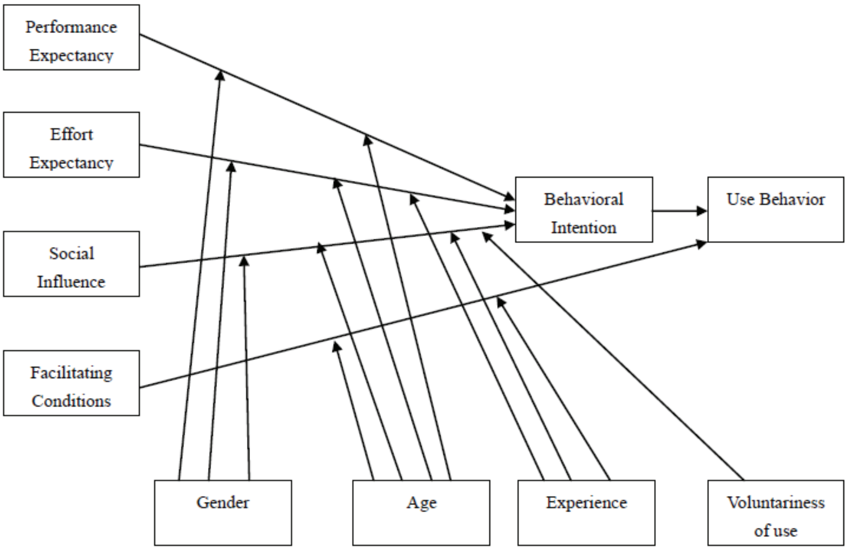


Figure 1: The UTAUT framework
Source: Venkatesh et al., 2003

The UTAUT framework, which includes constructs like “Performance Expectancy,” “Effort Expectancy,” “Social Influence,” and “Facilitating Condition,” is considered suitable for analyzing the dynamic and reciprocal interactions among individual, social, and technological systems of handloom weavers. In this study, it is crucial to comprehend the specific elements and intricate social dynamics of the handloom sector in order to effectively implement e-commerce and achieve its potential advantages. UTAUT incorporates both the social and psychological parameters, which increases its predictability and explanatory capacity and thus helps in comprehending the factors that affect the adoption of e-commerce by handloom weavers.

Methodology

The research study follows a qualitative methodology utilizing face-to-face interviews to collect data from handloom weavers. The semi-structured interview schedule was given to participants, and they were encouraged to elaborate on responses with pertinent and engaging details. Interviews were carried out in Gujarati (the local language) for an approximate duration of 45-60 minutes. The purposive sampling technique was utilized to allow the researcher to select participants that were in sync with the purpose, aim, and objective of the research undertaken (Campbell et al., 2020). It is an effective technique, as the study aims to generate a theory.

The researcher employed data saturation to determine the sample size, seeking information on the issue until no further insights could be gathered (Aldiabat and Le Navenec, 2018). A total of twelve people were considered eligible for the proposed study and were contacted individually. Following the ninth interview, no further information was acquired; hence, the sample size remained limited to nine respondents.

Data Analysis and Results

Data analysis was performed using two methods, the “Word Cloud” technique and the Grounded Theory methodology.

Word cloud

Data Visualization is an important tool used in contemporary science, facilitated by computers for qualitative research involving the collection of a large volume of textual data. The graphical depiction of data is essential for data visualization, allowing researchers to obtain structured and categorized data, which aids in the identification of underlying trends and the discovery of clusters essential for further analysis (Westby, 2022). The prominent terms in the “Word cloud” are those that have been reiterated multiple times. As the size of the words decreases, their frequency of recurrence in the analyzed documents lowers (Lohmann et al., 2015). Figure 2 illustrates the analysis of interview data from handloom weavers through a “Word Cloud.”

The word cloud in Figure 1 suggests that the term “e-commerce” is the boldest, suggesting it was used most frequently and served as the primary focus in the textual analysis of the interview data. The other most repeated terms in the analyzed texts include “online,” “media,” “adoption,” and “social,” which imply that the interviews revolved around the adoption of diverse e-commerce platforms for business and marketing. Numerous other terms, like “children,” “return,” “support,” “mode,” and “product,” regularly emerge, underscoring the necessity for assistance in embracing e-commerce and emphasizing the involvement of the younger generation in this venture. The relatively infrequent terms such as “customer,” “better websites,” “payment,” “challenges,” and “courier” suggest that participants perceived e-commerce websites as effective for engaging numerous customers, yet they lacked understanding of the processes involved in payment receipt and accurate product delivery to customers. Several additional terms, including "performance," "connectivity," "design," "selling," "problems," and others, were common; nevertheless, their representation in a lighter and smaller font indicates a reduced frequency of occurrence. The data reveals that participants discussed and cited variables related to e-commerce adoption and integration.

Figure 2: Word cloud
Source: Yadav, 2023

Grounded theory

The second method adopted for the analysis of the qualitative data is the grounded theory approach. Grounded theory is defined as "a general methodology of analysis linked with data collection that uses a systematically applied set of methods to generate an inductive theory about a substantive area" (Glaser, 2016). The coding and analysis of the transcribed codes was done utilizing the NVivo software and Microsoft Excel. The grounded theory is also referred to as thematic analysis, as the technique enables the formation of themes, similar to the critical analysis of the participant replies. This research employed thematic analysis to categorize the data according to various overlapping factors. This thorough analysis of the acquired data rendered the grounded theory technique effective for investigating the research subject at hand. Grounded theory has four stages: open coding, axial coding, selective coding, and theme integration, culminating in the formulation of theory (Yadav, 2023). Figure 3 illustrates the theoretical generation methodology employed in this research study.

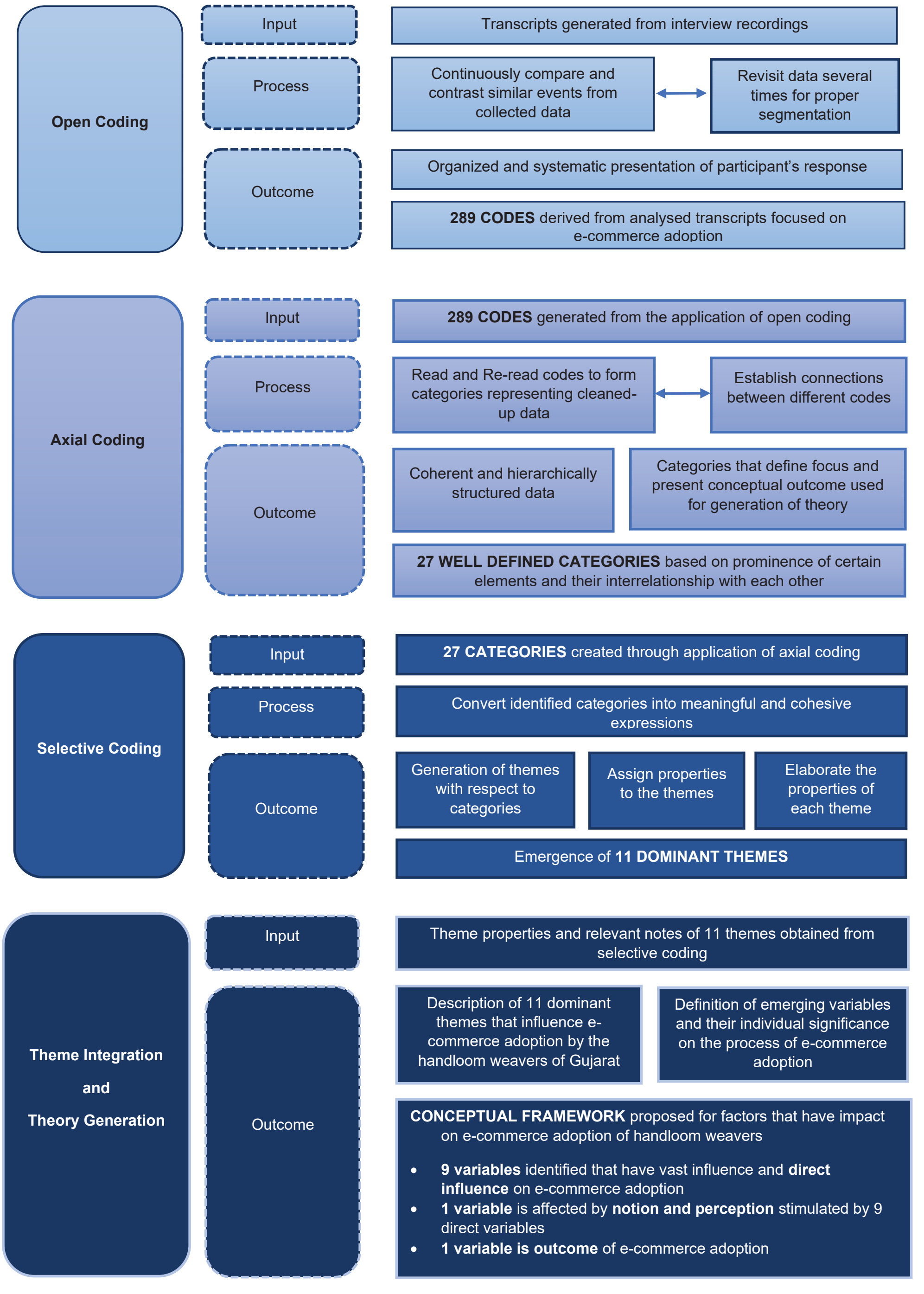


Figure 3: The coding process and codes generated

Source: Shubhangi Yadav

Results

The axial coding generated 27 categories, which were subsequently refined through selective coding, leading to the emergence of 11 dominant themes. Table 1 presents 26 categories and 10 themes: of these, 9 themes exhibit a significant and direct influence on the adoption of e-commerce; one theme, “Business Performance”, represents the outcome of e-commerce adoption; and the other theme, “Actual Adoption of E-commerce by Handloom Weavers”, has emerged as a dependent variable shaped by the perceptions and notions of the independent variables.

Table 1: Codes, Categories and Themes

S.No.	Codes	Categories	Themes
1.	Challenges of - Distinct inventory management for online and offline products. - Return problem due to variation in color. - Customers sometimes lie about the return.	Challenge of online customer management	**Barriers to Adoption**
2.	- Limited literacy, less knowledge. - Low proficiency in English. - The younger generation is disinclined to pursue a career in weaving.	Personal challenges	
3.	- Reliance on IT specialist. - Engaging with local courier for “Amazon” delivery. - The courier service presents significant challenges in certain rural areas.	Infrastructural challenge	
4.	- Challenges of communication in English. - Challenge of effective communication, especially when engaging with international consumers. - Challenges in drafting product description, etc.	Language challenges	
5.	Recurring expenses associated with e-commerce: - Professional photography services. - Annual budget for maintenance of website and server. - Purchase of IT equipment like computer, printer, etc. - Requirement of smart phone for selling on social media.	Financial challenges	
6.	- Insufficient technical expertise for online platforms and product promotion. - Inability to click quality photographs. - Challenges of internet connectivity in rural parts.	Technological challenges	

7.	- Children help with product photography and writing emails to the customer. - Children assist in e-commerce adoption. - Children operate and manage the online business. - Children embrace new technology and help to adopt it.	Helping hand of children	**Children Support**
8.	- We face challenges in online payment: "COD" reduces the risk associated with digital transactions. - Consumers are requested to transfer money to my account prior to dispatch. - The courier person is asked to hold the delivery until we confirm receipt of payment. - We are concerned that e-commerce mode is unsuitable for a cooperative society. - We are apprehensive about online security and associated risks. - We are apprehensive about frauds associated with internet-based platforms.	Risk of receiving money online	**Perceived Risk**
9.	- "Design Piracy" poses significant security concern: Handloom sari of Rs. 24,000/- is reproduced on power loom and sold at Rs.4,000/-. - Design plagiarism poses significant challenge with e-commerce and Instagram. - Designs are readily replicated.	Threat of design piracy	

10.	- Major returns arise due a discrepancy in color between the original item and the online image.
	- Potential chance of getting a damaged product upon return owing to "Amazon" 15-day return policy.
	- Minimal return attributable to "delay in delivery".
	- Customers infrequently report product flaws:
	  - Attributed to the fact that the items are handwoven.
	  - Advise them beforehand on the color discrepancies between the photograph and the actual product.
	- Minimal returns in home textiles and bath towels as
	  - Greater tolerance for shortcomings in this category.
	  - These are typically meant for household use.
	- There exists a risk of damage to products due to negligence by unprofessional transportation service.
		Risk of return;
		
		Risk of return of damaged product	

11.	- Adopting social media platforms such as "WhatsApp" yields superior outcomes and is more widely accepted.	Use of social media	**Relative Advantage**
12.	- Prior e-commerce knowledge is not essential. When connected with other digital marketplaces. - Challenging to maintain and sell through proprietary e-commerce platform. - In contrast to social media, the adoption of e-commerce incurs an annual recurring expense of Rs.30,000 to 40,000. - Weavers continually compare e-commerce with social media marketing.	Comparison Between social media and e-commerce	
13.	- Embracing social media for sales is quite straightforward. Prior e-commerce knowledge is not essential. It can be regarded as the starting phase of e-commerce adoption. - No investment or expenses associated with selling using social media applications. - Promotion using Facebook is more economical. - Customers usually never engage in deceit while purchasing over social media.	Advantage of social media	
14.	- E-marketplaces offer superior advantages compared to maintaining individual websites. - It is sufficient to own a smartphone for selling on e-marketplace.	Advantage of e-commerce over own website	
15.	- Trust concerns associated with Facebook and Instagram.	Disadvantage of social media	
16.	- I need to allocate more resources to improve the packaging for offline distribution.	Advantage of being online	
17.	- The government is advocating online marketing and e-payment methods; yet, there is a lack of governmental backing or legislation facilitating the adoption of e-commerce. - Adoption should be facilitated through training. We are confident that with proper guidance, we will successfully do online business. - The Weaver's Service Centre (WSC) acquainted us with e-commerce sales. - WSC registered us for the government portal and informed us about the advantages of social media.	Government support	**Institutional Support**
18.	- A login and password for e-commerce websites have been given to us. - "Amazon" does product photography at no additional cost.	B2B support	

19.	- Customers purchasing via online channels tend to be knowledgeable. They recognize the irregularities inherent in handmade products and hence exhibit greater tolerance for imperfections. - Have not encountered “returns”. Moreover, gained awareness of new payment options. - Certificates of authenticity foster trust. The “Handloom Mark” instils confidence in clients purchasing online.	Factors supporting adoption for better performance	**Behavioral Beliefs**
20.	- Importance of education: I lack the ability to adapt due to insufficient literacy. - Courier services are distant from our village, almost 20 km away. - The customer wishes to physically touch and feel the product	Factors hindering performance	
21.	- I learnt English to compose descriptions and producing videos for authenticity and trust. Initially it was challenging, but became manageable when got used to it. I used to aspire to work at this level, specifically selling on e-commerce. - Had we conceded earlier, we would have achieved more online sales. - Youth participation will improve performance. - I contacted “Jaypore.com,” which initiated my venture into e-commerce sales.	Activities performed for better outcomes	**Effort Expectancy**
22.	- Community support and derived inspiration from peers with their websites. - It required almost 1.5 years for me to be persuaded to embrace e-commerce and establish own website. - No one in the vicinity who has embraced e-commerce. - I was aware of e-commerce and observed others in my vicinity engaging in online business. - I joined “Facebook,” “WhatsApp,” and “Instagram” and inspired and motivated many others (possibly over 50) to embrace these platforms. - I continue to motivate and demonstrate to other weavers how to use online sales methods.	Influence of people from own/different working community	**Social Influence**
23.	- Reduced workload and reduced physical exertion. - Enhanced lifestyle. - More time for design development and product innovation with diverse yarns and colors.	Expected benefits	**Performance Expectancy**

	- Recognition and improved valuation for the craft. - Facilitated product promotion. - Optimal customer reach, direct engagement with clientele, broader consumer base.		
24.	- Reduced travel expense. - Reduced marketing expenditure; eliminate commission to intermediaries. - Additional costs like website maintenance, etc., incurred. The extra cost is less bothersome, as I am compensated. - I anticipate that e-commerce sales will rise in 1-2 years, which will lead to increased profits and a decrease in wholesale business. - My primary sale was to wholesalers; thus, no marketing cost was incurred. - We have engaged approximately 10-20 weavers due to the adoption of e-commerce; we now purchase more from other individual weavers.	Financial performance Market performance	**Business Performance**

Source: Yadav, 2023

Interpretation and Discussion

Table 1 depicts the conversion of the interview transcripts categorized with open coding into categories and dominant themes that emerged in the final phase.

The first theme was designated as "Barriers to Adoption." According to Wen, Harold and Pierrette (2019), the barriers to adoption refer to the limitations or constraints that are encountered by the individuals in transition to e-commerce. The study's findings suggest multiple barriers to e-commerce adoption, including technological constraints, where the weavers struggle to understand technology; linguistic barriers, where they cannot comprehend the operational language of e-commerce websites; financial barriers, where the weavers lack seed capital necessary for e-commerce investment; and infrastructural shortcomings, where they are unable to obtain the essential infrastructure for e-commerce adoption.

Certain codes were created that referenced children and highlighted how support from younger family members facilitated weavers in sending photos to customers, composing emails, and engaging in communication with them. Consequently, the category of children's assistance was classified under the theme of "Children Support," highlighting the importance of children in e-commerce adoption. When the weavers' offspring can implement technological advancements, the likelihood of shifting to e-commerce rises.

Gur and Turel (2022) assert that children's comprehension of technology can benefit the family business, as it enables them to readily acquire and exhibit technological proficiency.

The interview participants indicated various categories of risk, comprising concerns regarding online monetary transactions, security threats from online frauds, potential for design piracy, and the risk of customers returning damaged goods. This resulted in the emergence of a theme termed "Perceived Risk." Nguyen and Huynh (2018) assert that perceived risk and trust associated with e-commerce adoption are critical detrimental factors affecting individuals' intentions to engage in e-commerce adoption.

The interview responses featured multiple comparisons between social media and e-commerce adoption, resulting in the emergence of the fourth theme, termed "Relative Advantage." This theme emphasizes the comparison of social media with e-commerce, the advantage of social media relative to e-commerce websites, and the advantages and disadvantages of being online. Li and Ku (2018) define relative advantage as a motivating factor for the business owners to adopt e-commerce.

Multiple participants acknowledged the necessity for support in transitioning to and adopting e-commerce. Kraus, Kraus, and Osetskyi (2020) emphasize that expert support is crucial for the acceptance of new technology. Handloom weavers requested training and technical assistance from institutes such as NIFT, along with B2B support from e-marketplaces, to enhance their handloom businesses on e-commerce platforms, thereby easing the adoption process. This code was categorized under the category "Institutional Support."

Several codes identified certain attitudes among the participants regarding factors that promote or hinder the e-commerce adoption. For instance, the participants indicated that online shoppers are educated and exhibit a greater appreciation for handloom products. Conversely, they also perceived that lack of tactile interaction with the handloom fabric becomes a barrier to purchase. Darsono et al. (2019) defines behavioral belief as a conviction that a specific activity can result in a particular outcome or experience; thus, these codes were classified as "Behavioral Beliefs."

The participants discussed the activities they engaged in, such as acquiring proficiency in English or Hindi and mastering photography for online posting, to enhance e-commerce performance in their firm and achieve superior results. These acts pertain to the perceived level of effort required by the user to embrace e-commerce. The weavers may require increased efforts to integrate e-commerce due to their poor literacy levels, which hinder effective communication and abilities (Renu and Anupama, 2018). These discussions resulted in the formulation of the subject, “Effort Expectancy.”

Roethke et al. (2020) assert that expectations and perceptions of family and friends have an impact on an individual’s actions and decisions. When asked about weavers’ reasons for transitioning to e-commerce, participants cited the influence of e-commerce adoption on fellow handloom weavers within the community, exposure to urban environments, and assistance from family and friends. Therefore, the theme was designated as “Social Influence.”

The “Performance Expectancy” emerged as the ninth theme wherein the participants discussed the anticipated advantages of adopting e-commerce, such as reduced workload, enhanced lifestyle, increased time for design development, and reduced physical labor. According to Rahi et al. (2019), performance expectancy is the term used to describe activities that are carried out with the anticipation of achieving improved results. These are the favorable results and benefits that are recognized by the individual and would inspire the user to adopt e-commerce (Cui et al., 2019).

The research study by Alsaad, Mohamad and Ismail (2018) revealed that the choice to adopt e-commerce is shaped by individuals’ perceptions and attitudes regarding the associated risks, as well as their attitudes towards technology. This can be assessed by evaluating the time duration the handloom weaver dedicates to e-commerce activities. Therefore, the nine variables defined above have a significant impact and a direct correlation with the variable of “Actual E-commerce Adoption.”

The interviews also addressed the business performance following the adoption of e-commerce. The business performance is predominantly an outcome of e-commerce adoption, rather than a determinant that restricts or improves the e-commerce practices of handloom weavers. The business performance is affected by two factors—financial performance and market performance.

Numerous studies on e-commerce adoption have been evaluated for financial performance by analyzing criteria such as a higher sales percentage (Clayton and Criscuolo, 2002), sales growth, reduced transaction costs, and profit gains (Rahayu and Day, 2017). Consequently, the financial performance of the business will elucidate its capacity to generate money and financial returns for handloom weavers. Enhanced reach leads to improved revenue generation, which directly impacts the overall business performance.

The performance of businesses that have embraced e-commerce has been evaluated based on the growth of international and domestic markets, improved customer relationships (Clayton and Criscuolo, 2002), and some additional criteria. The market performance of a handloom weaver's business is dependent on the extent of their market presence and the degree of awareness about their handloom craft. It also affects the access of handloom weavers and their ability to provide handmade crafts to consumers worldwide.

Consequently, these emerging variables assist in the formulation of a conceptual model illustrated in Figure 4.

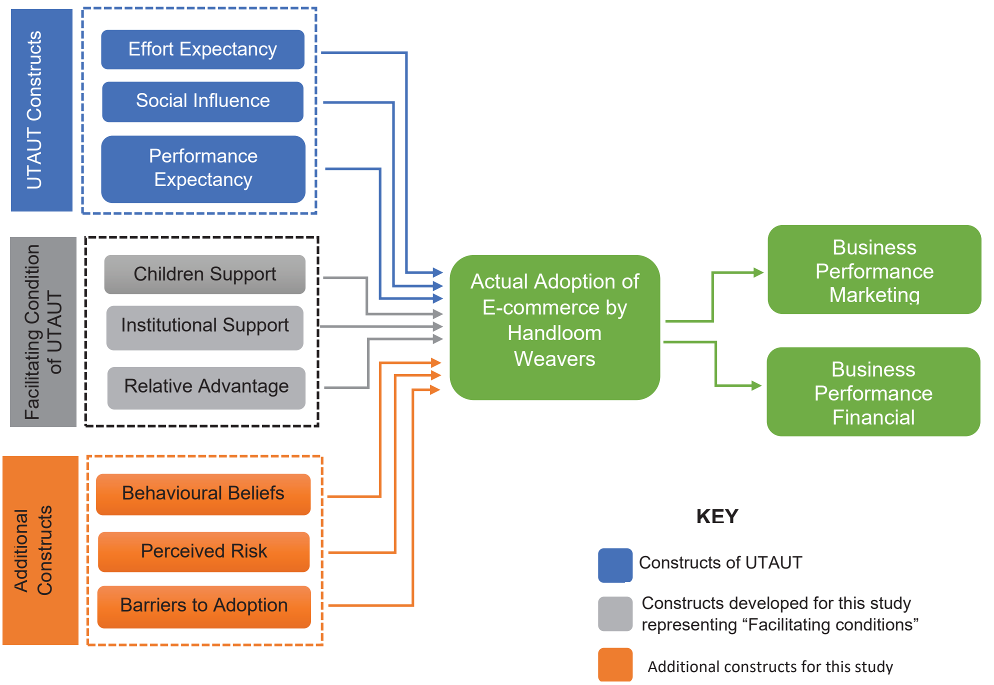


Figure 4: The conceptual framework

Source: Yadav, 2023

Conclusion

Figure 4 illustrates that nine variables strongly impact the "actual adoption of e-commerce by handloom weavers" (Yadav, 2023). The three original constructs of the UTAUT model are effort expectancy, social influence, and performance expectancy. Furthermore, three variables, children support, institutional support, and relative advantage, have emerged from this qualitative research and illustrate the "facilitating conditions" construct of the UTAUT model. Additionally, the remaining three constructs, behavioral beliefs, perceived risk, and barriers to adoption, have evolved in this study and are incorporated into the UTAUT model for assessing the e-commerce adoption of handloom weavers. These nine variables may exert either a positive or a negative influence on the "actual adoption" of e-commerce by the handloom weavers. The "Actual Adoption" in turn will influence the business performance of the handloom weavers in two aspects: the market performance and the financial performance. Consequently, a correlation is established between the components of UTAUT theory and the "Business Performance" of handloom weavers via "Actual E-commerce Adoption" (Yadav, 2023).

Implications

This research study makes a significant theoretical contribution by developing a conceptual framework that helps understand the factors influencing e-commerce adoption among handloom weavers, based on the UTAUT theory and enriched with themes from grounded theory and qualitative observations. By identifying 11 dominant factors—spanning both positive and negative impact—this study not only validates the relevance of existing UTAUT constructs but also proposes three context-specific constructs tailored to the unique socio-economic and technological environment of the handloom sector.

The implications of this study are multifaceted. For policymakers, the research points out the requirement for targeted digital literacy programs, infrastructural support, and trust-building mechanisms to encourage digital adoption among weavers. The inclusion of context-specific constructs like "children support," "institutional support," and "relative advantage" can guide the development of nuanced and culturally sensitive policy interventions. For industry stakeholders, the findings present an actionable framework for designing weaver-centric digital solutions. By recognizing both the technological and human aspects influencing adoption, businesses can co-create tools, marketplaces, and services that align better with the operational realities and value systems of traditional handloom weavers' communities. For academia, this research article presents findings from a qualitative strand of the author's doctoral research, restructured to advance a focused argument that contributes independently to the scholarly discourse. Further, this research can open new pathways in interdisciplinary research by extending the UTAUT framework to culturally rooted and informal economies.

To summarize, this study advances both theory and practice by offering a grounded, inclusive, and empirically informed understanding of digital adoption in the handloom sector, with the potential to drive sustainable growth and digital equity in India's craft economy.

References

Aldiabat, K.M. and Le Navenec, C. L., 2018. Data Saturation: The mysterious step in grounded theory method. *The Qualitative Report,* 23(1), pp.245-261.

Alsaad, A., Mohamad, R. and Ismail, N.A., 2018. The contingent role of dependency in predicting the intention to adopt B2B E-commerce. *Information Technology for Development,* 25(4), pp.686-714.

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D., and Walker, K., 2020. Purposive sampling: complex or simple? Research case examples. *Journal of research in nursing : JRN*, [e-journal] 25(8), pp.652–661. https://doi.org/10.1177/1744987120927206

Clayton, T. and Criscuolo, C., 2002. Electronic commerce and business change. *Economic Trends,* 583, pp.62-69.

Cui, Y., Mou, J., Cohen, J. and Liu, Y., 2019. Understanding information system success model and valence framework in sellers' acceptance of cross-border E-commerce: a sequential multi-method approach. *Electronic Commerce Research,* 19(4), pp.885-994.

Darsono, J.T., Susana, E., Prihnantono, E.Y. and Kasim, E.S., 2019. Strategic policirs for small and medium businesses in marketing through. *Entrepreneurship and Sustainability Issues,* 7(2), pp.1230-1245.

Ghosh, T., 2016. Weavers are the opportunity business needs: annapurna mamidipudi. *Mint,* [Online] Available at: <https://www.livemint.com/Leisure/m9HxAZYl8rKerbUcKbREHK/Weavers-are-the-opportunity-business-needs-Annapurna-Mamidi.html>[Accessed August 2024].

Glaser, B.G., 2016. Open coding descriptions. *The Grounded Theory Review,* 15(2), pp.108-110.

Granic, A., 2023. Technology acceptance and adoption in education. In: In: Zawacki-Richter, O., Jung, I., eds. *Handbool of Open, Distance and Digital Education.* Springer: Singapore.

Gur, D. and Turel, Y.K., 2022. Parenting in the digital age: attitudes, controls and limitations regarding children's use of ICT. *Computers and Education,* 183, pp.104-504.

Hada, J.S. and Chaturvedi, B., 2018. A study of the kota doria handloom cluster cluster, Rajasthan India. *Journal of Management Value and Ethics,* 8(1), pp.34-44.

Humbe, V.R., 2014. Role of social media in marketing of handloom products. *International Journal of Science and Research (IJSR),* 3(7), pp.136-139.

Kraus, N., Kraus, K. and Osetskyi, V., 2020. New quality of financial institution and business management. *Baltic Journal of Economic Studies,* 6(1), pp.59-66.

Li, C-Y. and Ku, Y-C., 2018. The power of a thums-up: will E-commerce switch to social commerce? *Information & Management,* 55(3), pp.340-357.

Lohmann, S., Heimerl, F., Bopp, F., Burch, M. and Ertl, T., 2015. Concentri cloud: word cloud visualization for multiple text documents. *19th International Conference on Information Visualisation*, Barcelona:Spain, pp.114-120

Majestic Mrss, 2016. *Report on market research for promotion of India handloom brand,* [pdf] Available at: <https://handlooms.nic.in/assets/img/INDIA%20HANDLOOM/2534.pdf> [Accessed 27th October 2025]

Mandal, S., 2015. Handloom Scenario of India: A case study of a renowned silk village in Mursidabad, West Bengal India. *The International Journal of Humanities and Social Studies,* 3(5), pp.65-70.

Minhas, A., 2024. *E-commerce in India - statistics & facts. Statista,* [online] Available at: <https://www.statista.com/topics/2454/e-commerce-in-india/> [Accessed September 2024].

Mishra, S.S. and Mohapatra, A.D., 2019. A Study on the present condition of the weavers of handloom industry: a review. *International Journal of Interdisciplinary Research and Innovations,* 7(2), pp.325-331.

Misra, S., 2019. An exploratory study on the problems of banarasi saree weavers. *Ayan,* pp.55-60.

Ministry of Textiles, 2022. *MInistry of textiles annual report 2021-22,*[pdf] Available at <https://texmin.nic.in/sites/default/files/AR_Ministry_of_Textiles_%202021-22_Eng.pdf> [Accessed 29th June 2025].

Nguyen, T.D. and Huynh, P.A., 2018. The role of perceived risk and trust on e-payment adoption. *Econometics for Financial Applications,* pp.926-940.

Rahayu, R. and Day, J., 2017. E-commerce adoption by SMEs in developing countries: evidence from Indonesia. *Eurasian Business Review,* 7(1), pp.25-41.

Rahi, S., Mansour, M.M.O, Alghizzawi, M. and Alnaser, F.M., 2019. Integration of UTAUT model in internet banking adoption context: the mediating role of performance expectancy and effort explectancy. *Journal of Research in Interactive Marketing.*13(3), pp.411-435.

Renu and Anupama, 2018. Digitisation: an aid in marketing handicrafts. *Journal of Emerging Technologies and Innovative Research,* 5(1), pp.294-296.

Roethke, K., Klumpe, J., Adam, M. and Benlian, A., 2020. Social influence tactics in e-commerce onboarding: the role of social proof and reciprocity in affecting user registrations. *Decision Support Systems,* 131, pp.113-168.

Sabarinathan, G. and Velamuri, S.R., 2020. GoCoop: Leveraging technology to impact the lives of the rural poor. In: L. Poonamallee, J. Scillitoe and S. Joy, eds. *Socio-Tech Innovation: Harnessing Technology for Social Good.* s.l.:Macmillan, pp. 223-238.

Sarkar, B., 2016. Impact of information communication technology on growth of handloom sector in West Bengal. *BVIMSR's Journal of Management Research,* 8(2), pp.47-55.

Varaganti, S., 2017. From local artisan to an online entrepreneur. *Mystory* [online] Available at: <https://yourstory.com/mystory/451a19c386-from-local-artisan-to> [Accessed 16 April 2024].

Venkatesh, J. and Kumarswamy, V., 2016. Impact of viral marketing on handloom products with special reference to coimbatore region. *International Journal of Research in Economics on Social Sciences,* 6(4), pp.1-8.

Venkatesh, V., Morris, M.G., Davis, G.B. and Davis, F.D., 2003. User acceptance of information technology: towards a unified view. *MIS Quarterly,* 27(3), pp.425-478.

Wen, L.Z., Harold, A.G. and Pierrette, C.T., 2019. Factors and barriers to adoption of e-commerce: the case of developing countries. *Journal of Entrepreneurship & Organization Managment,* 9(3), pp.114-125.

Westby, C., 2022. Comprehending multiple texts. *Word of Mouth,* 33(4), pp.9-12.

Yadav, S., 2023. *E-commerce adoption and impact on business performance of handwom weavers*, PhD thesis. National Institute of Fashion Technology.

About the authors

Shubhangi Yadav is currently the Chairperson of the Department of Textile Design at NIFT, India. Her PhD is on the subject of e-commerce technology adoption by handloom weavers. An Associate Professor at NIFT, Gandhinagar, she specializes in weave design and technology and computer-aided designing for textiles. She inspires the students to try different woven structures, experiment with yarns and colour patterns, and create innovative woven samples. Shubhangi also closely works with handloom weavers on consultancy projects in the handloom sector. She has conducted workshops on topics including design and colour sensitization, market awareness, and introduction to new marketing strategies like e-commerce and social commerce for the handloom weavers. She is hopeful that through her work and research, she can have a real impact at a grassroots level.

shubhangi.yadav@nift.ac.in

Binaya Bhusan Jena is Professor in the Department of Fashion Management Studies at NIFT, Bhubaneswar, and presently the Chairperson of the department. He has also served as the Director of NIFT, Bhubaneswar, and has been the Chairman of the Textile Association of India (TAI), Odisha unit, consecutively for three terms. He is widely popular as a sustainable fashion expert in the country and globally known for his “Farm to Fashion” concept and model. The Indian Parliamentary Standing Committee on Labour & Textiles appreciated his “Farm to Fashion” concept and recommended its implementation across all NIFT campuses. He has published and presented many research papers in numerous national and international conferences and seminars. He is a postgraduate in economics, has an MBA in marketing, and has done his MPhil and PhD at the School of International Studies (SIS), Jawaharlal Nehru University (JNU), New Delhi.

binaya.jena@nift.ac.in

Profiles of the Members of the Editorial Board

Ruby Kashyap Sood, Editor-in-Chief

Ruby Kashyap Sood is Professor in the Department of Textile Design at NIFT, New Delhi, and Head of the Publication Unit. With over two decades of teaching experience, her areas of specialization include surface design, craft studies, and textile art. She actively engages with the fashion industry for live projects to bring in experiential learning to the classroom. With a Master's in Textiles and Clothing from Delhi University, her doctoral research focuses on the Indian blouse. She has co-authored 'Celebrating Dreams: Weddings in India' and 'Anant: Sustainability and Circularity in Indian Handlooms' and co-edited 'Phulkari of Punjab: Celebrating Tradition and Transformation.' She has also co-authored the CBSE textbook, 'Traditional Indian Textiles.' Ruby has presented papers at prestigious conferences, published in reputed journals, and also serves as a reviewer for leading international journals. Her work contributes to design curriculum development, craft preservation, and the capacity building of artisans for social impact.

ruby.sood@nift.ac.in

Deepak Joshi, Associate Editor

Deepak Joshi has a PhD in management and is UGC NET-Management qualified. He has an FDP from IIM and a Master of Fashion Management degree from NIFT. He has over 15 years of experience in corporate and academic settings. He previously served as senior retail faculty at the FDDI, Ministry of Commerce and Industry, Government of India. His other significant stints include serving Future Group in various roles, such as brand relationship manager, assistant mall manager, and store manager. Currently, he is Assistant Professor in the Department of Fashion Management Studies at NIFT Delhi, the Unit Incharge of the Publication Unit, and also holds the additional responsibility of Joint Director at the NIFT Delhi campus.

deepak.joshi@nift.ac.in

Noopur Anand, Advisor & Member

Noopur Anand is an accomplished academician, researcher, and innovator with nearly three decades of experience at NIFT, where she currently serves as Dean (Academics). An authority in anthropometry, clothing, and textiles, she has led pioneering research in body sizing, smart garments, and wearable technology, and she holds a patent for a self-defense wearable device. Noopur has authored a book, contributed chapters to leading international publications, and published extensively in peer-reviewed journals. At NIFT, she has held several leadership roles, including Head of Research, Chairperson of Fashion Technology, and Head of Academic Systems. As Principal Investigator of Project INDIAsize, India's first national sizing survey, Noopur has advanced research that bridges science, design, and industry, fostering innovation, evidence-based development, and stronger academia–industry linkages in the Indian fashion ecosystem.

noopur.anand@nift.ac.in

Ling Zhang, Member

Ling Zhang is Associate Professor in the Department of Apparel, Events, and Hospitality Management at Iowa State University (ISU). Her primary research interests are wearable art design, creative design process, functional apparel design, sustainable apparel design, and pedagogy in apparel education. A doctorate, Ling's research aims to integrate theoretical frameworks from various disciplines into the apparel design process, complemented by quantitative or qualitative research methods. Her research strives to provide wearers with specialized functionality, catering to their specific needs. This includes aspects such as protection, assistance with body shape suitability, and addressing special requirements. Furthermore, she seeks to discover original and intellectual works that contribute to improving customers' lifestyles and bring about positive changes in how people engage with clothing and textiles. Ling has exhibited over 30 designs at national and international juried exhibitions and competitions, earning 20 design and research awards.

lzhang1@iastate.edu

Liz Barnes, Member

Liz Barnes is Head of the Manchester Fashion Institute at Manchester Metropolitan University and a leading expert in fashion production and consumption. Her research spans fast fashion, omnichannel consumer behavior, luxury fashion, and social media marketing. She has co-authored a seminal paper on fast fashion supply chains, cited over 800 times, and guest-edited two special issues on the topic. Liz's early work examined the UK fashion retail shift in the 2000s, and she remains a key voice in sustainability debates around fast fashion and is a Principal Investigator on the £6mn UKRI-funded Circular Fashion and Textiles Network Plus program. Widely published and internationally recognized, she is frequently invited to speak and contribute to media on fashion-related issues.

l.barnes@mmu.ac.uk

Binaya Bhusan Jena, Member

Binaya Bhusan Jena is Professor and the Chairperson of the Department of Fashion Management Studies at NIFT. With more than 22 years of experience, he has made immense contributions in the areas of research and training. He holds a Master's degree in Economics from Ravenshaw University, an MBA in Marketing from Pondicherry University, and an MPhil and PhD from Jawaharlal Nehru University. His areas of research interest revolve around sustainable fashion, Indian traditional knowledge, and international trade. He has supervised many PhD scholars at NIFT. Binaya has represented NIFT as a board member in various government bodies and industries, including Chairperson of the Textile Association of India, Odisha; Board Member of the SERIFED, Govt. of Odisha; Member of the Working Committee on Sustainable Textiles Policy; and Member of the Consultative Committee of the Geographical Indications Registry. He is also a UGC Chairman's nominee to the Executive Council of KIIT University and a Senate Member of Ravenshaw University.

binaya.jena@nift.ac.in

Binwant Kaur, Member

Binwant Kaur is Professor at NIFT, Kolkata. Her academic and professional journey reflects her commitment to sustainability, textiles, and information technology in fashion. Her doctoral research was in the field of comfort properties of handloom union fabrics, with a focus on selecting the best alternatives through optimization techniques. Throughout her 28-year academic journey at NIFT, she has focused on integrating IT tools into fashion education and research. As a visiting scholar in 2014 at the Graduate School of Fashion Institute of Technology, New York, she pursued her research in 3D printing in fashion and the impact of RFID technology in apparel supply chains. Binwant has authored several research papers and delivered expert lectures at Buffalo State University, LIM College, and Hunter College in New York, USA. In addition to her long-standing academic role, she has served in leadership positions at NIFT, including Director, NIFT, Kolkata; Head of International and Domestic Linkages; and Chairperson of Fashion Technology.

binwant.kaur@nift.ac.in

Malini Divakala, Member

Malini Divakala, a dedicated academician with over three decades of teaching experience, currently serves as the Director of the NIFT, Hyderabad. She is also Professor and former Chairperson of the Department of Fashion Design at NIFT. Trained at FIT, New York, and an alumnus of MS University, Vadodara, her deep passion for Indian art and culture shaped her doctoral research on the Kalamkari tradition of Andhra Pradesh. Throughout her career, Malini has been deeply engaged in research, contributing to international journals, conferences, and books, and mentors students in exploring design interventions in fashion with a strong focus on textile crafts. Her latest publication, “Painted and Printed Textiles of the Coromandel Coast,” was published by the Kalakshetra Foundation, Ministry of Culture, Government of India. In addition, she has authored a CBSE textbook on fabric studies and compiled a volume on the GI crafts of Andhra Pradesh and Telangana.

malini.divakala@nift.ac.in

Martin Jeyasingh Mathews, Member

Martin Jeyasingh Mathews is Professor and Chairperson of the Department of Fashion Communication at NIFT. An enthusiastic, creative, and optimistic educator, he earned his PhD in Fashion Forecasting and Information Technology from the Bharath Institute of Higher Education and Research, Chennai. He serves as a doctoral committee member at the Bharath Institute of Higher Education and Research and Anna University, Chennai, and a NIFT-listed PhD supervisor. He was an external examiner for a PhD at AMET University, Chennai. Martin has been associated with NIFT for over two decades, during which he has held several key roles, including Course Coordinator and Unit Incharge. He has undergone international training in graphic design and integrated media skills at SCAD, Hong Kong. His research focuses on fashion forecasting and data mining in the apparel sector, and his work has been published in peer-reviewed journals and presented at national and international conferences.

martin.mathews@nift.ac.in

P. Mohanraj, Member

P. Mohanraj is Professor and Chairperson of the Department of Knitwear Design at NIFT. He holds a PhD in Fashion Apparel Retail and is a Chartered Textile Engineer (India). With three decades of experience spanning industry, administration, academics, research, and consultancy, he brings in-depth expertise in fashion knitwear, merchandising, and retail. At NIFT Chennai, he has held various positions as Course Coordinator of Knitwear Design and Textile Design, Regional Industry Coordinator, International Linkages Coordinator, and Project In-Charge. He has successfully conceived and executed several design projects, in addition to creating and launching continuing education and short-term programs. Mohanraj's specializations include computerized flat and circular knitting, fashion marketing and merchandising, and retail. He has published extensively in national and international journals and has undertaken training in Japan, as well as visits to leading fairs and exhibitions in London, Germany, and Singapore.

mohanraj.palanisamy@nift.ac.in

Preetha Hussain, Member

Preetha Hussain holds the position of Professor of Design at NIFT, New Delhi. Her areas of teaching and research encompass fashion, body and adornment, design thinking and strategy, experiential design and spaces, lifestyle trends and forecasts, transdisciplinary aspects of cultural studies, and design education. She has been invited as a faculty researcher for a specialized program for Master's in Strategic Design (DIMI) at Politecnico di Milano, Italy. Preetha believes that transdisciplinary learning is crucial and integrates her interest in socio-cultural perspectives with the fields of fashion and design. She has contributed as a key design expert in the realm of color forecasting for Asian Paints color trends workshops, and she has presented papers on varied platforms. She has also been invited by DC (Handicrafts) as a jury member for the empanelment of designers and handicraft awards. As the Chairperson of the Foundation program, she has engaged in curriculum and pedagogic development.

preetha.hussain@nift.ac.in

Rashmi Gulati, Member

Rashmi Gulati is a distinguished academician, researcher, and industry expert with over 26 years of experience in teaching, research, and professional practice. She is currently Chairperson of the Department of Design Space, leading the Master of Design program at NIFT. She holds a PhD in Management, and her doctoral research culminated in the development of a comprehensive sustainable model framework for the arts and crafts sector in Mumbai. Her areas of expertise include craft studies and sustainability, design thinking, and creative thinking, along with proficiency in digital graphics, personal branding, self and society, and professional ethics. Rashmi has made significant contributions to NIFT over nearly three decades, successfully managing diverse leadership roles. She has a strong track record of fostering industry connections, spearheading live-classroom initiatives, and bridging the gap between academia and industry practices. Her research contributions, particularly in the domain of craft and sustainability, have been published in esteemed national and international journals.

rashmi.gulati@nift.ac.in

Sabyasachi Sengupta, Member

Sabyasachi Sengupta is Associate Professor and an alumnus of NIFT Kolkata (MFTech) and Visva Bharati University (PhD). He is the recipient of the National Scholarship and worked in the apparel industry before joining academia. He has been associated with academics for over twenty-five years, teaching design disciplines in the areas of apparel design, design ergonomics, luxury theory, craft practices, and culture. He is particularly interested in apparel, fashion language and systems, luxury, and ergonomics. He has published many national and international papers on fashion-semiotics-linguistics, fashion reading, textile semantics, and Tagorian studies in 'Texts-Textiles-Textuality,' relocating Bengal's textiles' evolutionary journey and socio-cultural anecdotes (India in general and Bengal in particular) through cross-disciplinary approaches. He has also written and is passionate about textiles' empiricism and textiles' phenomenology. Sabyasachi creates both hand-drawn and digital illustrations for NIFT promotions and various visual platforms. He also writes and edits for children, encouraging them to engage with textile-reading.

sabyasachi.sengupta@nift.ac.in

Sanjeev Sadashiv Malage, Member

Sanjeev Sadashiv Malage is Professor in the domain of consumer behavior and neuromarketing at NIFT, Bengaluru. He joined NIFT in 2003 as Assistant Professor and has worked at various NIFT campuses and departments. His current teaching and research areas include marketing management, consumer behavior, neuromarketing, and strategic management. He obtained his PhD from Gulbarga University in advertising and consumer behavior. Sanjeev has served as Centre Coordinator for the Department of Fashion Management Studies for two terms and as Nodal Officer for Admissions for two years at NIFT Bengaluru, in addition to being a member of various other committees. He also served as the Head of International Linkages at the NIFT Head Office and Cluster Initiative Coordinator at various NIFT campuses. He has presented and published papers at numerous reputable conferences.

sanjeev.malage@nift.ac.in

Shubhangi Yadav, Member

Shubhangi Yadav is currently the Chairperson of the Department of Textile Design at NIFT, India. Her PhD is on the subject of e-commerce technology adoption by handloom weavers. An Associate Professor at NIFT, Gandhinagar, she specializes in weave design and technology and computer-aided designing for textiles. She inspires the students to try different woven structures, experiment with yarns and color patterns, and create innovative woven samples. Shubhangi also closely works with handloom weavers on consultancy projects in the handloom sector. She has conducted workshops on topics including design and color sensitization, market awareness, and introduction to new marketing strategies like e-commerce and social commerce for the handloom weavers. She is hopeful that through her work and research, she can have a real impact at a grassroots level.

shubhangi.yadav@nift.ac.in

Vandita Seth, Member

Vandita Seth is Professor and former Chairperson of the Department of Fashion Design at NIFT. Her journey at NIFT Gandhinagar with the Department of Fashion Design, since its inception, has been an exceptional phase of 28 years. She has held various posts at NIFT Gandhinagar, like Course Coordinator of Fashion Design, International and Domestic Linkages Coordinator, and Internal Design Consultant for SGSY projects, to name a few. Vandita completed her graduation and master's from the Maharaja Sayajirao University of Baroda in Clothing and Textiles, followed by a PhD from NIFT, New Delhi. She has undertaken a fellowship program at the Fashion Institute of Technology of New York. She has worked on and coordinated various design projects. She has presented research papers and has widely traveled in India and abroad to attend fashion fairs, shows, and lectures. She specializes in the subjects of the history of Indian textiles, Indian craft studies, draped garments, and sustainable products.

vandita.seth@nift.ac.in

Varsha Gupta, Member

Varsha Gupta is Professor in the Department of Design Space at NIFT, New Delhi, and is presently Head of the Research unit. She has almost 30 years of experience in industry and academia. In 2014, she was awarded a doctorate by NIFT for her research titled 'Recycling of Post-Consumer Textile Waste and Developing a Model for Sustainable Development using System Dynamics.' She completed her MSc in Textiles and Clothing at Lady Irwin College, Delhi University, and received training at the Fashion Institute of Technology (FIT), New York. Varsha has been an external expert member on the Programmatic Review Panel at the Limerick School of Art & Design, Limerick Institute of Technology, Ireland. She has presented papers at international conferences in London, Leeds, and Brussels, and a video based on her doctoral work was screened at the PhD festival in Milan, Italy.

varsha.gupta@nift.ac.in

Vibhavari Kumar, Member

Vibhavari Kumar is a space designer and design educator based in Bengaluru. She holds a bachelor's degree in Architecture from the NIT, Tiruchirappalli, and a PhD from Jain University, Bengaluru, where she researched the socio-cultural impact of the Bengaluru Metro on people and spaces. She currently serves as Professor in the Department of Fashion Communication and as Chairperson of the Department of Fashion Interiors at NIFT. Her academic journey reflects a deep engagement with geometry and an interdisciplinary approach that connects space, fashion, socio-cultural studies, and psychology, which she actively explores through innovative design pedagogy. Vibhavari's research interests center around design thinking within the Indian context. During her doctoral studies, she contributed to an ICSSR-funded project and co-authored three chapters for a book. She was also a core committee member of the conference "Contemporary Issues and Trends in Urban Transformation." She has authored and presented several papers at both national and international forums.

vibhavari.kumar@nift.ac.in

राष्ट्रीय फैशन प्रौद्योगिकी संस्थान
National Institute of Fashion Technology

Celebrating
40 years of NIFT

www.nift.ac.in

ISSN 2583-5262

NIFT HEAD OFFICE: NIFT CAMPUS, HAUZ KHAS, NEW DELHI - 110 016