Kaunas University of Technology
Faculty of Mechanical Engineering and Design

QR-Based Durable Labeling for Digital Product Passports in Fashion Industry

Master's Final Degree Project

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Kaunas, 2026

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Given to the student

Mehedi Hasan

(Name, Surname)

1. **Title of the Project**

QR-Based Durable Labeling for Digital Product Passports in Fashion Industry

(In English)

Patvarus ženklinimas QR kodu skaitmeniniam produkto pasui mados pramonėje

(In Lithuanian)

2. **Aim and Tasks of the Project**

Aim: To develop a practical system for implementing Digital Product Passport (DPP) in the fashion industry, utilizing durable QR codes and a web-based data model to ensure accessibility, simplicity, and long-term usability.

Tasks:

1. To analyze EU ESPR (Ecodesign for Sustainable Products Regulation) and DPP requirements for textiles.
2. To compare QR, RFID, and NFC technologies used for labelling in the fashion industry and determine the most reliable option.
3. To experiment with QR code application on fabrics, evaluating their usability and durability under different conditions.
4. To develop and demonstrate a simplified DPP system using QR codes linked to a web-based interface hosted on Google Sites.

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Mehedi Hasan. QR-Based Durable Labeling for Digital Product Passports in Fashion Industry. Master's Final Degree Project, supervisor Assoc. Prof. Dr. Jurgita Domskienė; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Polymers and Textiles Technologies (F02), Technological Sciences (F).

Keywords: digital product passport (DPP); sustainable fashion; circular economy; traceability; QR code durability; textile labeling.

Kaunas, 2026. 65 p.

Summary

This study develops and tests a practical Digital Product Passport (DPP) solution for the fashion industry by combining durable QR-code labels on textiles with a simple, low-cost web system. The work responds to EU ESPR-related expectations that product information should be transparent, standardised, and available throughout the product lifecycle. A review of QR codes, RFID, and NFC shows that QR codes are the most appropriate option for consumer use because they are inexpensive, can be scanned with any smartphone, and require little supporting infrastructure, while RFID and NFC typically involve higher costs and more complex implementation.To examine performance under realistic conditions, an experimental programme assessed QR durability and long-term scannability on a 100% polyester knit fabric. Version 2 QR codes (25×25 modules) were produced in several physical sizes and applied using sublimation printing, heat transfer, and embroidery. The samples were exposed to domestic washing and tumble drying in line with ISO 6330 and to cyclic tensile loading in both fabric directions in line with ISO 20932-1. Readability was then evaluated using a controlled smartphone-scanning procedure consistent with ISO/IEC 15415 quality principles, supported by an ImageJ-based assessment of QR distortion.The findings show that long-term digital accessibility depends mainly on the application method and the minimum QR size. Sublimation remained reliably readable at sizes of 20 mm and above, and heat transfer stayed fully readable within the tested 30–50 mm range. Embroidery performed worst: readability decreased after mechanical loading and washing, and very small codes (10 mm) did not provide dependable scanning. Finally, a DPP prototype built with Google Sites, cloud-hosted data, and dynamic QR access demonstrated that structured product information can be presented clearly, updated in real time, and accessed across devices, offering a feasible pathway for cost-constrained SMEs.

Mehedi Hasan. Patvarus ženklinimas QR kodu skaitmeniniam produkto pasui mados pramonėje. Magistro baigiamasis projektas, vadovė doc. dr. Jurgita Domskienė; Mechanikos inžinerijos ir dizaino fakultetas, Kauno technologijos universitetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Polimerų ir tekstilės technologijos (F02), Technologijos mokslai (F).

Raktažodžiai: skaitmeninis gaminio pasas (DPP); tvari mada; žiedinė ekonomika; atsekamumas; QR kodo patvarumas; tekstilės ženklinimas; gyvavimo ciklo informacija.

Kaunas, 2026. 65 p.

Santrauka

Darbe buvo sukurtas ir išbandytas praktiškai pritaikomas skaitmeninio produkto paso (DPP) sprendimas mados pramonei, derinant patvarų QR kodo ženklinimą su nesudėtingai mažomis sąnaudomis realizuojama internetine informacine sistema. Darbas parengtas atsižvelgiant į ES Tvarių gaminių ekologinio projektavimo reglamentą(ESPR), pagal kurį informacija apie gaminį turi būti skaidri, standartizuota ir prieinama visą gaminio gyvavimo ciklą. QR kodų, RFID ir NFC technologijų apžvalga parodė, kad QR kodai yra tinkamiausias vartotojams sprendimas, nes yra nebrangūs, nuskenuojami bet kuriuo išmaniuoju telefonu ir reikalauja minimalios papildomos infrastruktūros, o RFID ir NFC ženklinimas dažniausiai susijęs su didesnėmis sąnaudomis ir sudėtingesniu diegimu. Siekiant įvertinti QR kodų patikimumą realiomis naudojimo sąlygomis, buvo atliktas eksperimentinis tyrimas, kuriuo buvo tirtas QR kodų ant 100 % poliesterio mezginio patvarumas ir ilgaamžiškumas . Tyrimams buvo naudojami 2 versijos skirtingo dydžio QR kodai (25×25 moduliai), kurie buvo ant tekstilės užnešami trimis skirtingais būdais, pritaikant sublimacinę spaudą, terminio perkėlimo būdą ir siuvinėjimą. Bandiniai buvo skalbiami ir džiovinami pagal ISO 6330 bei veikiami ciklinėmis tempimo apkrovomis abiem medžiagos kryptimis pagal ISO 20932-1. Kodų nuskaitymas vertintas panaudojant skenavimo išmaniuoju telefonu metodiką, suderintą su ISO/IEC 15415 reikalvimais, o QR kodo iškraipymai papildomai įvertinti taikant vaizdų analizę ImageJ programa. Rezultatai parodė, kad patvari skaitmeninė prieiga priklauso nuo pasirinktos technologijos ir QR kodo dydžio. Sublimacijos būdu pagaminti QR kodai yra patikimai nuskenuojami, kai jų dydis ≥20 mm, o terminio perkėlimo būdu gauti QR kodai nuskenuojami, kai dydis yra 30–50 mm. Siuvinėjimas parodė prastesnius rezultatus: po mechaninio poveikio tempimu ir skalbimo QR kodo nuskaitomumas sumažėjo, o labai maži kodai (10 mm) neužtikrino patikimo skenavimo. Darbe DPP prototipas buvo sukurtaspanaudojant Google Sites, su debesijoje saugomais duomenimis ir dinamine QR prieiga. Veikiantis prototipas parodė, kad struktūruotą gaminio informaciją galima aiškiai pateikti, atnaujinti realiuoju laiku ir patogiai pasiekti įvairiais įrenginiais, taip sudarant įgyvendinamą sprendimą ribotus išteklius turinčioms mažoms ir vidutinėms įmonėms.

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Abbreviations:

DPP – Digital Product Passport;

EN – European Norm (European standard);

EPRS – European Parliamentary Research Service;

ESPR – Ecodesign for Sustainable Products Regulation;

EU – European Union;

GHG – Greenhouse Gas(es);

IEC – International Electrotechnical Commission;

ImageJ – Image analysis software;

ISO – International Organization for Standardization;

LCA – Life Cycle Assessment;

NFC – Near Field Communication;

QR – Quick Response (code);

RFID – Radio Frequency Identification;

Introduction

Fashion is not just about style; it is also a major source of environmental harm, with around 10% of global emissions and high levels of waste. Rapid production cycles, resource abuse, and ineffective waste management systems have made the environmental footprint of this industry even worse. The global awareness of sustainability and climate change is now very high, and companies increasingly prioritise environmentally responsible business models. A key driver of this change is the European Union's Ecodesign for Sustainable Products Regulation (ESPR), which aims to make product lifecycles more environmentally sustainable. In parallel to these regulatory moves, there has been a growing interest in a technological solution that DPPs (Digital Product Passport) could offer a sustainable product traceability and transparency tool in the fashion sector [1].

Digital Product Passports (DPP) give an unprecedented insight into a product´s complete cycle from the sourcing of raw materials to the disposal of goods. By enabling more granular details around products for tracking, manufacturing, and recyclability, this digital framework supports the principles of a circular economy. DPPs can facilitate the recycling of fabrics for innovative, high-value textile recycling in the fashion industry and support the management of hazardous substances as well as assist brands and consumers in making more sustainable choices about products. Through transparency on materials, processes and disposal possibilities, DPPs are in line with the principles of the European Green Deal and the EU circular economy agenda [2].The contents of research are designed to analyse the EU ESPR and textile sector-specific requirements for the implementation of DPPs. The research further investigates different labelling technologies such as QR codes, Radio Frequency Identification (RFID) and Near Field Communication (NFC) and their contribution in facilitating DPPs. The EU ESPR means all products must be manufactured with sustainability at their heart such as being resource-efficient and recyclable with reduced environmental footprint. It will significantly transform the textile industry, forcing companies to adopt a transparent and sustainable way for product manufacturing processes [3]. Even better, knowledge of how DPPs are aligned with this is key to enabling fashion companies to fulfil sustainability requirements and stimulate real-world developments of the circular economy.

Labelling systems are essential for the implementation of DPPs, as these systems provide consumer and industry stakeholders access to timely product-related information. QR codes, RFID, and NFC technologies all come with their own strengths and weaknesses, especially when considering cost, ease of use, durability, and how much information they can store. The QR codes are often used as they are inexpensive and easy to use (they can be scanned by any mobile device)[4]. However, they still raise a big question mark about durability when used on textiles.

In this work, the above-mentioned labelling technologies, especially QR codes, are compared to see how effectively they perform in the fashion industry. Key factors such as washing, and tensile behaviour are examined to understand how durable and practical QR codes are when applied to textile materials. The aim is to determine which sustainability labelling method is most reliable for fashion products throughout the consumer journey. More specifically, the experimental process is carried out to observe how abrasion, washability, and tensile forces influence the scannability and overall performance of QR codes over time [7]. In addition, a DPP system is simplified and utilized, using QR codes to connect to a web-based interface on Google Sites. This demonstration shows how DPPs can be implemented in practice giving fashion brands a way to scale solutions for product data management and increase consumer transparency. It is also illustrative for how DPPs can contribute to a more circular economy by facilitating product information availability for re-use, recycling and disposal. The goal of this research is to provide further elucidation on the subject and potentially lead toward the emergence of durable systems of labelling within the domain of fashion. Through analysis of policy frameworks, tech solutions and real-world applications the work helps navigate the fashion industry towards achieving its sustainability objectives with a more transparent circular economy.

Aim: To develop a practical system for implementing Digital Product Passport (DPP) in the fashion industry, utilizing durable QR codes and a web-based data model to ensure accessibility, simplicity, and long-term usability.

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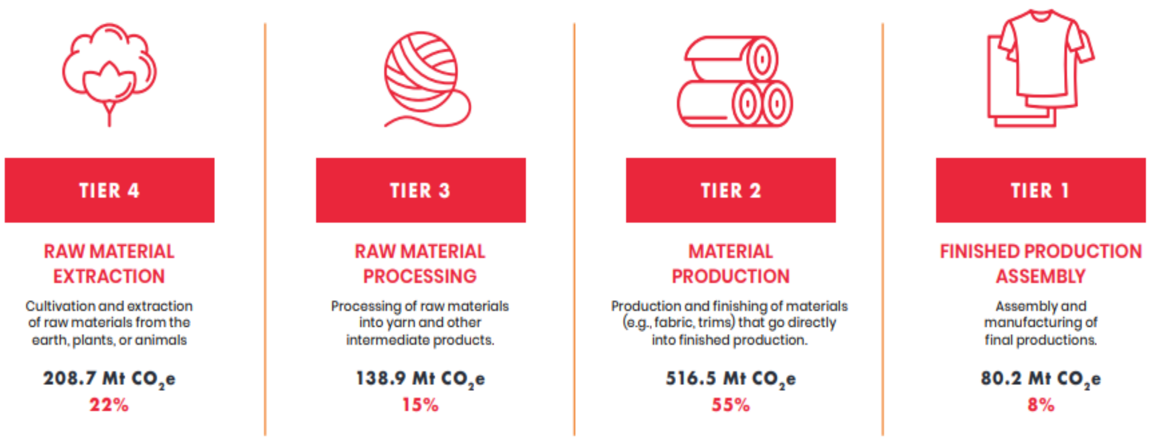
1. Literature Analysis

1.1. The Importance of Sustainability in Textiles

The global economy has seemed to be positively impacted by the textile industry, which includes fibers, clothing production, and clothing retail, because of the international supply chain engagement the industry. This industry plays an important role in the GDP of every country. But, the sudden growth because of global demand and fast fashion has severely impacted the industry's environment, social, and economic standards. Depletion of the resources for the coming generations is strived to be avoided through sustainability practices such as minimizing labor conditions, loss of the diminishing resources, and long-term economic viability. Adoption of ethical supply chains, and use of circular and eco-friendly materials is necessary. Without diminishing the resources for the coming generations, the economic strands take pride for the sustainability practices while exploiting the resources. The contribution of the textile industry to the world's environmental degradation which is estimated to be between 8-10% of global carbon emissions, impact the industry in greater perspective than even the aviation and sea shipping combined [5]. The impact emanates from all the stages of the textile life cycle, from extraction to disposal, and is glares from the production phase itself. The impact is glaring from issues of water consumption and pollution, generation of GHG and along with the production of wasteof 9.52 tons of CO2 per global ton of polyester [6].



Note: 1 million tonnes = 1 million tonne (Mt), 1 billion tonnes = 1 gigatonne (Gt)

Fig. 1. Emissions Breakdown Across Tiers, 2023 [7]

Cotton and other synthetic fibers, are primary contributors to microplastic pollution with an estimated 700,000 microfibers released per wash which cumulatively spills into the ocean on a global scale. Out of the total water pollution, land area, and raw materials, garments are one of the leading contributors, with the EU being responsible for 2-10% of the overall garment pollution [8]. Worldwide production of fiber has rapidly increased, which has increased the overall impact of pollution.

1.2. Ecodesign Requirements for Textiles

The ESPR (Regulation (EU) 2024/1781) provides a single legal framework that should promote the environmental sustainability of any products put on the EU market. In this context, textiles are recognized as one of the priority groups because of their tremendous impacts on the environment, which is estimated to contribute 8 to10 percent towards the total carbon emissions globally and excessive use of water and resources. The ESPR is based on the principles of the Circular Economy Action Plan and the European Green Deal requiring the transition to more sustainable, repairable, and resource-efficient products [9]. In case of textiles, the regulation stipulates ecodesign rules, which comprise the entire product life cycle, i.e. from the extraction and production of material to its use, reuse and recycling [1]. Detailed technical requirements of these requirements shall be given out through delegated acts relating to textiles. Nevertheless, the fundamental pillars of sustainability, such as durability, repairability, recyclability, and resource efficiency, have already been formulated as a binding principle.

1.2.1. Durability and Lifespan Extension

The sustainability goals of ESPR revolve around durability. It also confirm that goods used are viable and last longer before putting them out of use hence minimizes consumption and the generation of wastes. Documentation that comes with the ESPR stresses that renewal or replacement is only impact the expiry of the intended lifespan of a product a concept referred to as the Stratum Doorn approach [10]. This policy urges producers to enhance the material strength, fabric resilience and design quality, thereby increasing product life and decreasing the amount of waste on the environment due to frequent replacement. Empirical evidence has indicated that enhancing the durability of garments is directly proportional to carbon footprints since the environmental impact per use is low when products are in circulation longer [3]. Therefore, the ESPR requires that the durability test be conducted, performance indicators, and labelling systems should be used to ensure that the consumer makes an informed decision and the producers will have an incentive to design products with longer durability.

1.2.2. Reusability and Repairability

The second core element of ESPR textile ecodesign is repairability. It demands the products to be designed in such a way that they can be maintained and repaired with the help of easily accessible parts and modular structures. Manufacturers are required to provide spare parts, repair manuals and technical details to enable garments to be repaired easily instead of disposa [1]. This helps in achieving the EU circular economy, by encouraging local repair services and cutting the waste of textiles. The regulation decreases the carbon and material intensity in the sector by prolonging the useful lifespan of the sector by repairing and refurbishing their products [9]. One example of how this can be achieved is by using repair-friendly components, such as standardized fasteners and zippers. This makes it easier for consumers to use the product for a longer time and also supports secondary markets for repair, reuse, and resale. Over time, this can lower the need to produce new textiles and lower the overall environmental impact of the sector. It also creates new business opportunities for local SMEs in repair, alteration, and upcycling services, supporting more sustainable regional economies.

1.2.3. Recyclability and Circular Material Use

ESPR (Ecodesign for Sustainable Products Regulation) requires textile companies to design products for recycling and circular use of materials, so textiles can be recycled and fibres recovered [9].This is to encourage the use of single-fibre compositions or fibre blends that can be separated easily to enable fibre-to-fibre recycling. Compliant materials like organic cotton and recycled polyester, which can be made out of post-consumer plastics, are also noted as examples to be highlighted because they can decrease reliance on virgin fibres and promote the use of circular material loops.The increased recyclability will reduce the amount of waste produced, lower the total lifecycle emissions of the textile manufacturing and disposal [8]. Moreover, the ESPR incorporates the concept of recyclability in labelling and the next Digital Product Passport (DPP) to provide an open communication of the content of the materials and the potential for recyclability.

1.2.4. Material and Resource Efficiency

Resource efficiency is a principle that supports the above-mentioned requirements and is aimed at the reduction of water, energy and chemical consumption throughout the textile value chain. The ESPR encourages the use of materials and processes that minimize the environmental burdens- including dyeing processes with low impact, energy-efficient manufacturing, and the introduction of renewable materials. Organic cotton and other organic fibres can reduce the use of chemical pesticides by up to 90 % and water use by up to 50 % compared with conventional cotton.. Equally, recycling of post-consumer fibres consumes 30 to 40 % less energy than when virgin fibres are produced [11]. The ESPR balances the upstream reductions of production effects with improvements in durability and recyclability by designing products to incorporate material efficiency metrics in their design requirements. In combination, these ecodesign initiatives are aimed at decelerating material flows, prolonging the life-cycle of products, and minimizing total environmental footprints, which place the textile industry at the center of Europe shifting to a circular economy [3]. Moreover, resource efficiency strengthens the relationship between product design and sustainable production systems, which provides that the efforts made at the material level, should be transferred into quantifiable environmental benefits across the whole value chain.

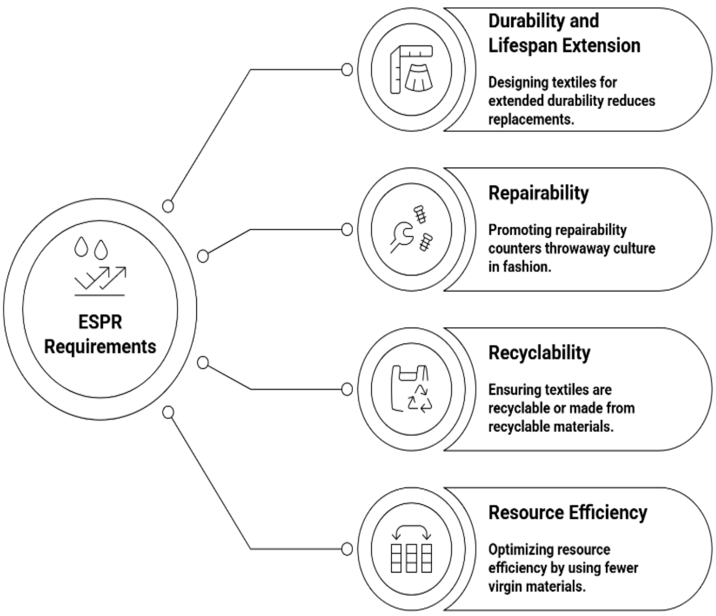


Fig. 2. Illustration of ESPR requirements

ESPR simultaneously integrates lifecycle-based efficiency measures, which also facilitate industrial innovation, compelling the manufacturers to switch to cleaner technologies and adopt the circular supply chain models. This shift promotes the objective of the EU to achieve climate neutrality by

2050, as well as makes the European textile manufacturers more competitive on the global scale by lowering their costs through efficiency and raising their environmental performance.

1.3. Digital Product Passport (DPP)

The DPP has been designated by the Ecodesign Regulation of the European Union for Sustainable Products as an indispensable tool in institutionalizing product traceability and circularity. With the performance delegated act for textiles, the type of information required by DPP mandates standardised machine-readable data about product materials and ingredients, repairability and recyclability, along with environmental Life cycle cost analysis indicators. In the form of QR codes or RFID tags, the DPP can be read and recorded by stakeholders, manufacturers, recyclers, dealers, and consumers. Information such as fiber content, source of raw materials or chemicals used are only a scan away. How to repair or recycle products is also included [12]. This system aims to achieve data interoperability, facilitate recycling operations more efficiently, assist repair technicians in their endeavors and offer easy access by regulatory authorities to verify compliance in real time. Integrated with a corporation's system for sustainable development, DPP information supports the reporting of environmental, social and corporate governance performance, promoting transparency as well as responsible business administration. By linking product design and end-of-life management, the DPP makes the circular economy real and in line with the principle of data-driven sustainable development which lies at its core [13]. Recent analyses indicate that Digital Product Passports are set to revolutionize the retail sector by giving every product a reliable digital ID, which in turn boosts transparency and promotes circular practices throughout supply chains.

1.3.1. Role of Digital Product Passport in Reducing Environmental Impact in Textiles

Digital Product Passports (DPPs) play a crucial role in minimizing the environmental impact of the textile sector by facilitating access to lifecycle information, such as material content, sourcing regions and recyclability instructions. Such transparency provides the opportunity for stakeholders (manufacturers, recyclers, or consumers, etc.) to make informed decisions that contribute to the efficient use of resources, waste reduction, and compliance with circular economy principles [1]. DPPs enable the efficient tracking and management of textile products to ensure a real-time change in compliance with EU Ecodesign for Sustainable Products Regulation (ESPR) by linking machine-readable data that can be accessed through indirect means like the QR code or RFID tag [9]. By introducing durability, repairability, and recyclability indicators in DPPs which prevent a high consumption of resources and emissions during the life cycle of textiles, these instruments promote eco-design. For example, the ability to recycle fiber-to-fiber helps limit the consumption of virgin materials, either cotton, which requires around 2720 litres of water per T-shirt produced, or polyester, which creates 9,52 tons of CO_2 per ton produced. DPPs enhance the longevity of products by offering repair manuals and ensuring access to spare parts, thus reducing waste and repeated replacement of the product, thereby reducing the associated carbon footprints [14].

DPPs also contribute to more effective waste management by simplifying recycling via clear identification of recyclable materials and hazardous substances, in the context of the EU Circular Economy Action Plan. This nurtures closed-loop systems of textile reuse or repurposing, which divert tons of waste textiles away from landfills every year, as well as diverting almost 700000 microfibers per wash from entering global water systems and resulting microplastic pollution[15]. DPPs help brands and consumers make more sustainable choices by providing data-backed decision-making tools, and driving transparency, and thereby aligning with EU climate policy ambitions. DPPs also enable the quantitative validation and validation of carbon emission cuts through the provision of empirically validated datasets of constituent materials, manufacturing processes, and supply chain logistics. The given framework is a prototype of mathematical transformation of DPP data into more practical sustainability information.

For an example, A fashion manufacturer produces 10,000 polyester shirts in Bangladesh for European markets, specifically Lithuania. The implementation of a Digital Product Passport reveals critical carbon hotspots and enables targeted sustainability interventions The implementation of DPP provides a detailed, data-rich breakdown of the product's lifecycle, allowing the company to make targeted, high-impact decisions to reduce its carbon footprint.
Core Variables

1. $n = 10{,}000$ Pieces Production quantity
2. $CF_v = 9.2$ kg Carbon footprint per unit (virgin materials) [16]
3. $CF_r = 5.5$ Kg Carbon footprint per unit (recycled materials) [17]
4. $\Delta CF_{material} = CF_v - CF_r = 3.7$ kg Material substitute savings
5. $\Delta CF_{transport} = 1.5$ kg Logistics optimization savings

Transport Savings Derivation ($\Delta CF\_transport$)
Let's mathematically derive the transport savings:
Given:
Distance: $d = 6{,}000$ km approximately (Bangladesh to Lithuania)
Weight per shirt: $w = 0.3$ kg = 0.0003 t
Air emission factor: $EF_{air} = 850$ g CO_2e/t-km
Sea emission factor: $EF_{sea} = 10$ g CO_2e/t-km

DEFRA 2023 Carbon Footprint Data[18]

I. Air Freight (Long Haul): 0.85532 kg CO_2e per tonne-kilometer
II. Sea Freight (Transoceanic): 0.00997 kg CO_2e per tonne-kilometer

Air Transport Emissions:

$$CF_{air} = w \times d \times EF_{air} \quad (1)$$

$$CF_{air} = 0.0003 \times 6{,}000 \times 850 = 1{,}530 \text{ g} = 1.53 \text{ kg}$$

Sea Transport Emissions:

$$CF_{sea} = w \times d \times EF_{sea} \quad (2)$$

$$CF_{sea} = 0.0003 \times 6{,}000 \times 10 = 18 \text{ g} = 0.018 \text{ kg}$$

Transport Savings:

$$\Delta CF_{transport} = CF_{air} - CF_{sea} \quad (3)$$

$$\Delta CF_{transport} = 1.53 - 0.018 = 1.512 \text{ kg} \approx 1.5 \text{ kg}$$

Mathematical Proof

1. Baseline Emissions Calculation

$$E_b = n \times CF_v = 10{,}000 \times 9.2 = 92{,}000\ \text{kg}\ CO_2e \quad (4)$$

2. Optimized Emissions Calculation

$$E_n = n \times \left(CF_v - \Delta CF_{material} - \Delta CF_{transport}\right) \quad (5)$$

$$E_n = 10{,}000 \times (9.2 - 3.7 - 1.5) = 40{,}000\ \text{kg}\ CO_2e$$

3. Reduction Verification

4. Absolute Reduction:

$$\Delta E_{total} = E_b - E_n = 92{,}000 - 40{,}000 = 52{,}000\ \text{kg}\ CO_2e4. \quad (6)$$

5. Mathematical Validation

$$\text{Reduction}\ \% = \frac{3.7+1.5}{9.2} \times 100 = \frac{5.2}{9.2} \times 100 = 56.5\% \quad (7)$$

The use of Digital Product Passport (DPP) achieved a measurable meaningful change in the footprint of carbon involved in the production line of polyester shirt. The interventions based on data led to a total reduction of 52,000 kg CO 2e, which is equal to the reduction of 56.5% of the total baseline. This development was mainly fuelled by two major developments one Material Substitution (71% of saving) and another Recycled polyester. Logistics Optimization (29% of savings) by switching to sea transportation. This example shows that DPPs transform sustainability as a conceptual dream to a quantitatively verifiable and reportable model.

1.3.2. Chapter Summary

The textile sector is one of the most polluting sectors in the world and is a leading global contributor of carbon emissions, freshwater consumption, and pollution. While delivering the adverse impacts, the business should transition to sustainable habits together with making use of eco-friendly supplies and ensuring ethical provide chains in order to alleviate these impacts. The ESPR regulation of the EU aims to increase longevity, refurbishability, recyclability and resource efficiency of textiles. They aid in prolonging the lifespan of items, minimizing waste, and advancing the utilization of recyclable substances such as organic cotton and recycled polyester. Another important element to support sustainability is the DPP. And it offers straightforward, easy-to-understand information on the content of a product and its recyclability to enable better decisions in a circular economy for manufacturers, consumers, and recyclers alike.

To conclude, it is important that sustainable practices are integrated into all parts of the clothing supply chain. It is a vital part of the industry’s framework in order to lower the impact and induce change to a circular economy. The ESPR and the DPP legislation now recognise this.

DPP will represent detailed digital records that document the environmental life cycle of a product throughout its lifetime.

2. Theoretical Analysis

2.1. Comparative Analysis of Labelling Technologies: QR, RFID, and NFC

The ESPR EU 2024/1781 makes Digital Product Passports (DPPs) a key tool for integrating sustainability and circularity into the textile value chain, with labelling technologies being the crucial interface between the physical products and the digital databases [1]. This part reviews compliant labelling solutions by considering the application of Quick Response (QR) codes, Radio-Frequency Identification (RFID) and Near Field Communication (NFC) followed by an outline of the regulatory laboratoryelling regulations and demand on these technologies in the context of traceability, transparency and lifecycle management for textiles [2]. These needs, based on the information obligations of ESPR and in line with the objectives of the EU Strategy for Sustainable and Circular Textiles, call for a hybrid physical-digital approach to reduce environmental impacts but also to provide stakeholders access from manufacturers and recyclers to consumers . The EU ban on unsafe chemicals threatens to drive non-complying entities from the market, highlighting the urgent need for potential fast durable technologies capable of phased implementation by 2027 onward [9].

2.2. Labeling Standards for Textile DPP under the EU Ecodesign Regulation

The DPP under ESPR will require detailed rules on product identification and data availability. Under Articles 12-14 of the regulation [9], the obligation to integrate new machine-readable durable data carriers to be placed on textile products, packaging aor accompanying documents in the form of digital identifiers, physical labels or embedded elements It acts as a bridge between the physical and digital worlds and provides the basic architecture to enable circular economy principles along the whole textile value chain.

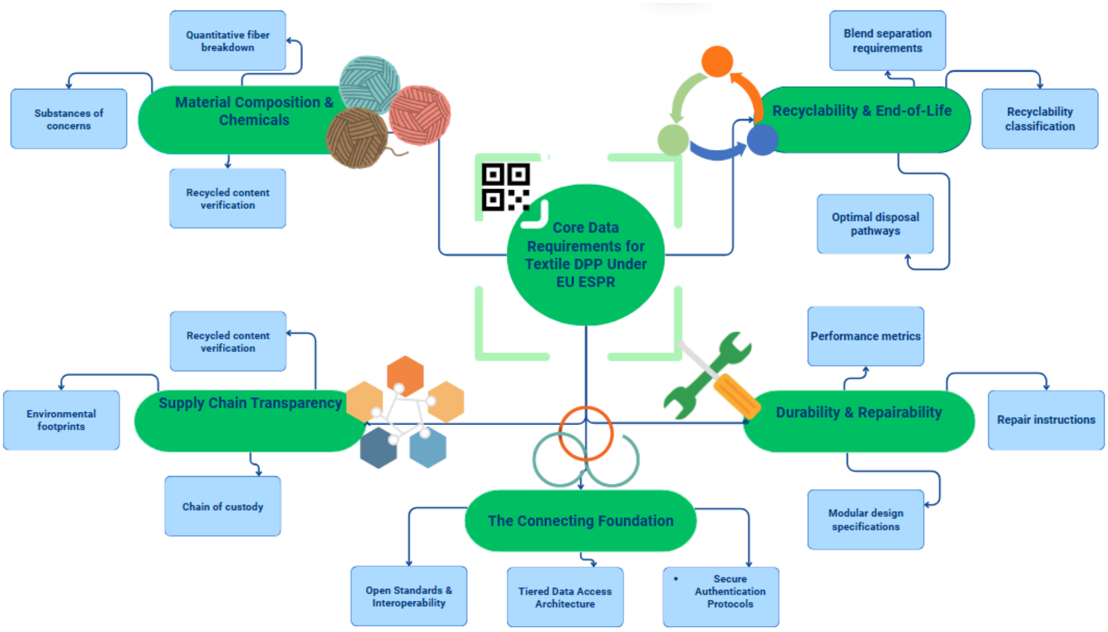


Fig. 3. The circular value chain in DPP

Research on DPP architecture has recognised five fundamental data domains for outlining labelling requirements. These domains reconfigure traditional labelling from static carriers of information to active governing interfaces for sustainability, allowing multi-stakeholder engagement across circularity initiatives from design to post-consumption functions [19].

2.3. Comparative Analysis of QR, RFID and NFC

This comparative analysis explains the possibility of QR codes, RFID, and NFC technologies to promote the DPPs in the fashion industry in line with the ESPR that is projected to be implemented in 2030. The complexity of the supply chains and the heterogeneity of the stakeholders that are unique to the fashion industry make the choice of the right technology crucial to achieving regulatory compliance at once and enhancing innovation. The study examines important factors, such as price, longevity, storage capacity, ease of use by consumers, and high complexity of integration, as well as security and range of readability features. The results outline the strengths and weaknesses of each technology in question, hence giving insightful information on how effective these technologies are in terms of promoting sustainability and operational effectiveness in the context of the fashion industry [4].

Table 1. Comparative Analysis of QR, RFID, and NFC Technologies for Textile DPPs [4, 20, 21]

Criteria	QR Code	RFID (UHF)	NFC
Unit Cost	Very Low (€0.01–€0.05 negligible printing)	Medium (€0.05–€0.15 bulk passive up to €10+ active)	High (€0.10–€0.40 specialized integration)
Reader Required	Ubiquitous smartphone camera (no app)	Dedicated RFID interrogator (€50–€500)	NFC-enabled smartphone (post-2011 ubiquity)
Read Range	Visual proximity (0–2 m line-of-sight)	Extended (up to 10 m non-line-of-sight)	Proximal (≤ 10 cm tap-based)
Data Capacity	Low (up to 3 KB URL gateway to cloud)	High (up to 8 KB onboard archival)	Medium (up to 4 KB bidirectional flux)
Durability	Moderate to High (10–50+ washes laser/embroidery variants excel)	High (IP68 200+ washes, 180°C tolerance)	High (IP68 200+ washes, tamper-evident)
Consumer Accessibility	Very High (universal 95%+ global smartphones)	Very Low (industrial silos consumer exclusion)	High (tap simplicity 80%+ penetration, but device-dependent)
Data Security	Low (static replication-prone)	Medium (encryptable unidirectional)	High (cryptographic anti-cloning safeguards)
Integration Complexity	Low (print/embroidery backend URL linkage)	High (middleware frequency harmonization)	Medium (sew-on/iron-on app ecosystems)
Primary Strength	Inclusivity, scalability, thrift	Automation, provenance auditing	Interactivity, authenticity
Integration Forms	Printed on labels, hang tags, fabric embroidered, laser etched, heat transfer logos.	Embedded in woven labels, denim, sewn pouches, laminated for water resistance, RFID yarn.	Embedded in linings, accessories, iron-on labels, sewn button, tags,heat transfer labels with

2.3.1. QR Code

The incorporation of QR codes into Digital Product Passports (DPPs) for the textiles industry is a clear example of this synergy between physical product identification and digital data management that will provide an important link in the circular economy. A QR code is a data carrier whereby the encoded image is not the totality of a Unique Product Identifier (UPI), but rather is a mere pointer-like item- a unique serial number or a direct URL. The hierarchical structure of the graphical items in the code does not entrench embedded product information instead, it acts as a reference key to the decentralized digital twin of the product [22]. The entire data of the twin is stored and maintained on a state-of-the-art cloud system, which is safeguarded by advanced cryptographic algorithms that encompass quantum-resistant authenticated encryption algorithms.Its strategic application is powered by a compelling order of factors: its near zero cost and ability to be printed on any substrate scalable to millions; the near-ubiquitous scannability across consumer smartphones for unparalleled downstream data access, and the fact that it can iteratively update the linked DPP content such as adding new repair tutorials, change-of-ownership records or end-of-life recycling options without editing the physical tag, thereby future-proofing a product's approval footprint. For the consumer, this makes the purchase more than just a transaction it becomes a way to stay connected.

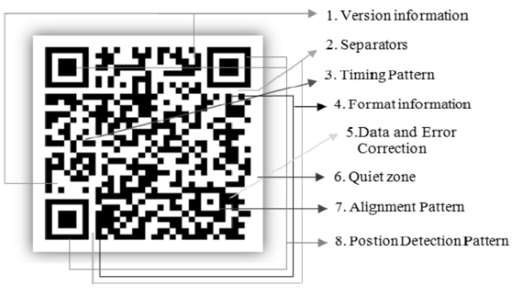


Fig. 4. Structure of QR code [22]

They can easily see where the garment came from, what it's made of, and how it impacts the environment. Propellor also helps in another project by making lifecycle management simpler and promoting transparency, so consumers can make better, more informed choices. However, the value of this system is based heavily on a solid backend ensuring data integrity, against tampering and respecting standardized data schema (e.g., as per regulations like EU's ESPR) to allow for interoperability across brands and recyclers. As a result, it is the QR code that rises above being just a hyperlink: It is the key touchpoint to set in motion an entire ecosystem of trust, transparency and circularity an autonomous but functionally interdependent life within our mission for the modernisation and transformation of a global textile industry.

2.3.2. RFID (UHF)

RFID (Radio Frequency Identification) is an identification system that uses radio waves for object detection and tracking, RFID includes two main parts: the RFID tag (including data), may be small wireless devices or labels, and the reader device to read the attached information [23]. In textiles, RFID tags can be used in clothing where they are capable of recording vital details of the place and date of manufacturing, material composition or care recommendations to simplify recycling. Information can be obtained at different levels: in the production environment, during distribution in the retail chain, as well as in end-of-life-recycle loops giving RFID a measurable benefit to product management along the product lifecycle.

RFID advantages for DPP the textile case there are many reasons why RFID is a strong candidate for use in DPP in textiles. RFID Improves traceability with direct real-time tracking of the product throughout the supply chain. It provides better durability RFID tags are prepared to be able to withstand wear and tear and exposure through various environments so that the data accessibility is maintained [24]. RFID further enables a more sustainable life cycle for textiles, with more items being easily recycled or upcycled at the end, supporting a circular economy. What this means for shoppers is that RFID tags provide visibility, insight and traceability on where a product comes from, what's in it and how much of an impact it will have.

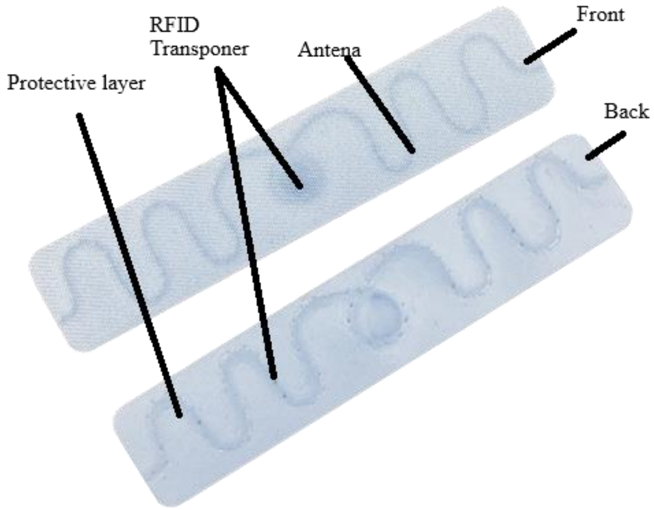


Fig. 5. Structure of RFID (Textile tag)

Nevertheless, there are obstacles to RFID deployment in the textile sector. For example, smaller manufacturers may be unable to afford the cost of adopting RFID solutions, such as tags, readers and software. There are also privacy implications as the RFID tags can be read at a distance, which could compromise product or consumer information to unauthorized parties. Though RFID tags are robust, they do not remain unaffected by washing and wearing under severe conditions, creating difficulty in terms of long-term use for textile applications. Moreover, textile supply chain stakeholders' reluctance to accept the system can discourage its widespread use which can prevent the industry from wholeheartedly welcoming this technology [25]. Nevertheless, RFID has the potential to greatly enhance efficiency, transparency and sustainability in textile products.

2.3.3. NFC

In the case of textile DPPs, NFC technology provides the unique advantage of converting every garment into an interactive platform. This is not just traceability, but also a way for brands to create a long-lasting relationship with the customer. A tap could offer styling tips, link to repair services, or create an easy resale mechanism, all after the point of sale [26]. This active user connection is essential to building a circular economy urging reuse and product longevity in contrast to the previous linear "buy & throw away" model.

From a security perspective, NFC data access can be performed in a more secure and controlled manner than can be done with other types of RFID. The necessity of physical proximity is therefore built in privacy protection and guarantees that a digital passport cannot be read surreptitiously from afar [27]. In fact, sophisticated NFC tags can even use encryption and password protection features to give brands control over sensitive supply chain data, while remaining transparent and freely sharing broader sustainability credentials with consumers. This type of layered security is crucial in defending business intelligence and consumer privacy.

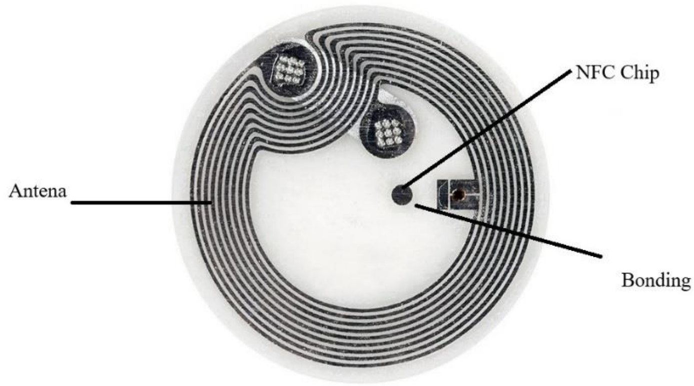


Fig. 6. Structure of NFC (Passive tag)

One of the major roadblocks for industry-wide standardization in the successful adoption of NFC-based DPPs. For the system to operate smoothly between brands, recyclers and resale platforms, uniformity on data formats, secure transmission of such data and physical placement of the tags must be agreed upon. Without this shared frame of reference, the digital ecosystem will be siloed, which makes the DPP less useful. To unlock this potential, players in the industry would need to work together to establish universal standards ensuring that a garment articulated via an NFC tap delivers value across its entire lifecycle and for each stakeholder in the circular chain.

2.3.4. QR Code as the Optimal Tagging System for Garment DPP

Out of all tagging technologies, such as QR Code, RFID, and NFC, the QR Code seems to be the most practical and scalable solution to a Digital Product Passport in the garment industry. It is mostly due to the technology's simplicity, affordability, and universality. Unlike RFID or NFC systems that require expensive chips and specific readers, QR codes can be cheaply printed on the labels or the packaging and easily scanned with any smartphone [21]. Therefore, technology becomes accessible not only to the manufacturers and retailers but also to the customers and recyclers alike, forming the eco-system of information flow that is fully transparent and inclusive. Functioning as a digital bridge, a QR code establishes a connection between the physical garment and its digital twin in the cloud where the owner can view and modify data about the product's material composition, repair procedure, ownership history, recycling options, and more. Notably, this can be done without the need to tamper with the physical tag, making technology the most sustainable and future proof of all. From a practical standpoint, QR codes are extremely cost efficient, infinitely scalable to the number of products, and add no electronic waste as a resultESPR (Regulation (EU) 2024/1781, which comes into effect on July 18, 2024) replaces Directive 2009/125/EC, and it effectively extends ecodesign in order to place requirements on durability, repairability and recyclability on nearly all physical products [1]. Also, it states that Digital Product Passports (DPPs) must contain standardized, machine-readable information attached to unique product identifiers in order to ensure that repairers, second-hand sellers, refurbishers, and other stakeholders can access the necessary data efficiently can all access the data safely and conveniently in the product life cycle. A QR scan also significantly heightens the buyer experience by expanding simple purchase with information on the product's origin, material composition, and environmental impact. This ensures not only circularity but also gives the user knowledge to make a more responsible and conscious purchase.

In comparison, although RFID is more traceable and NFC offers more means of security, both systems are less available due to prohibitive costs and lack of infrastructure, as well as the lack of devices that are able to read those tags that are not prevalent in the current state. As a result, for the garment industry processes as they currently appear, QR code seems to be the perfect solution that fills the niche of functionality, availability, and viability of implementation for a flexible, circular, and transparent fashion.

2.3.5. Chapter Summary

This chapter examines and comparatively analyses three relevant labeling technologies, which include the QR codes, RFID technology, and the NFC technology with respect to the DPP as stipulated in the ESPR (Regulating (EU) 2024/1781) [1]. These technologies are an indispensable nexus of tangible fabrics and their online equivalents, which helps in promoting increased traceability, transparency, and circularity across the textile value chain. The comparative analysis has been done with the consideration of factors like price, longevity, storage capacity of data, interoperability and accessibility of consumers. The results have shown that, in spite of the significant benefits of RFID and NFC in traceability, automation, and data security, the relatively high cost, as well as the requirement of a specific infrastructure, reduce their viability in large-scale adoption in the garment industry. On the other hand, the most economic, adaptable, and open option is a QR code. They are cheap to make, can be printed on labels and can be scanned using any smart phone hence making them accessible to all the stakeholders, including manufacturers and retailers, consumers and recyclers. The fundamental purpose of the DPP, namely the ability to offer a standardized and machine-readable information that can be updated and made available over the lifetime of a product, also serves QR codes well to contribute technical performance as well as consumer experience, as it allows access to product provenance, composition of materials and how to repair it as well as its impact on the environment. In general, this chapter concludes that QR codes are the most viable and efficient option when it comes to applying the Digital Product Passport in garments and achieving the success of blending technological simplicity with the larger goals of sustainability as provided by both the ESPR and the European Union vision of a transparent and circular textile economy.

3. Experiment Methodology

3.1. Research Objective

The objective of this experimental investigation is to evaluate the durability, readability, and visual quality of QR codes applied to textile material for use in Digital Product Passport (DPP) applications. The study examines whether QR codes remain scannable and maintain their shape and structure when the textile is stretched or washed, and assesses visual changes through normal evaluation. Deformation and recovery of the QR-coded textiles will be tested according to ISO 20932-1:2018 [28], while wash durability and adhesion will be evaluated following ISO 6330:2012 [29]. QR code readability will be assessed using ISO/IEC 15415:2011 [30], and functional scannability will be tested with smartphone scanners under controlled conditions. This investigation aims to determine the suitability of QR coded textiles as a reliable medium for wearable DPP systems, ensuring long-term functionality and compliance with EU sustainability and traceability requirements.

3.2. QR Code Design and Generation

A QR code was generated using the online tool 'TQRCG. The code is a standard black-and-white square containing an embedded URL.

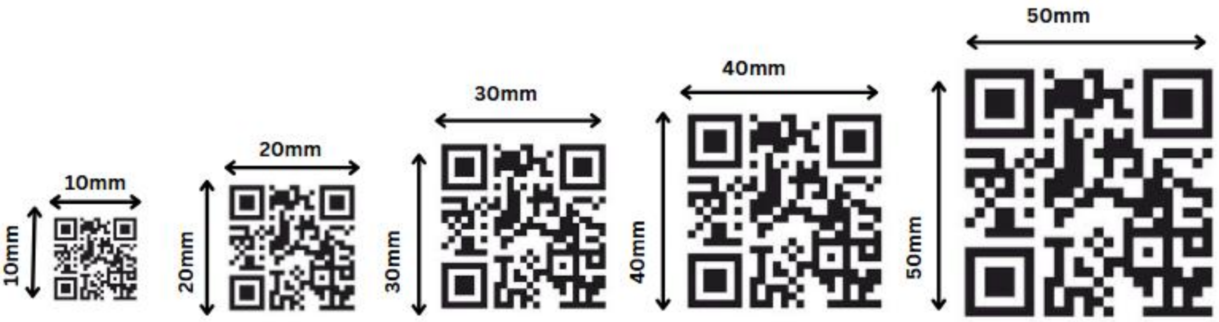


Fig. 7. QR code in different sizes

Table 2. Chosen QR code specification

Specification	**Details**
Version Number	2
Module Size (Grid)	25 × 25 modules
Data Capacity – Numeric	44 characters
Data Capacity – Alphanumeric	27 characters
Data Capacity – Byte Mode	17 bytes
Data Capacity – Kanji	10 characters
Number of Alignment Patterns	1
Alignment Pattern Position	(18, 18)
Error Correction Levels Available	L (7%), M (15%),
Finder Patterns	3 (top-left, top-right, bottom-left)
Timing Patterns	Horizontal & vertical between finders
Version Information	Not included until Version 7+

For this experiment, five different sizes 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm were selected for embedding onto the textile material. Version 2 QR codes with a 25 × 25 module structure were used to provide adequate data capacity while keeping the codes compact enough for printing on fabric. Multiple sizes were chosen to evaluate how QR code dimensions affect scannability, durability, and visual clarity when applied to stretchable textile surfaces.

3.3. Material

For this experiment, the chosen textile material is a weft knitted, interlock knit fabric.The composition of this material is 100% polyester, which is suitable for printing QR code with various techniques. This white fabric provides a smooth, flat surface for implementing the 25 × 25 module grid of a Version 2 QR code. Polyester like this are widely used, forming about 30–40% of materials in the sportswear and outdoor apparel market, valued at $193 billion in 2023 [31].

Table 3. Chosen material specification

Material	Parameters	Specification
	Fiber composition	Polyester
	Knit type	Interlock knitted
	Fabric weight	175 g/m^2
	Thickness	0.42 mm
	Edge Stability	No edge curling
	Color	White

Polyester, making up roughly 55% of global textile fibers, is durable and resists sunlight, water, and wear [32]. The white color ensures the black QR code modules stand out for clear scanning. The interlock knit's similar front and back sides allow even printing. Due to the fabric's stretch, higher QR code error correction levels are needed to maintain readability when the material is stretched.

3.4. QR Code Implementation Methods

In this experiment, three well-known textile image integration methods, namely embroidery (E), heat transfer (T) printing, and sublimation (S), were used to embed QR code images in fabric materials. These methods are widely implemented in the textile and apparel industry and work on well-defined technical requirements depending on the composition of fibers and processing conditions. Stitched structures in finished fabrics were used to apply the QR code pattern via embroidery. The result is the combination of appropriate embroidery machines, optimized stitching parameters, controlled operating speed, and the use of appropriate auxiliary materials, which is the key to accurate and high-quality code reproduction. Table 4 shows the specific equipment configuration, digital software environments, and other processing parameters needed to successfully integrate QR code images into the selected textile substrates. These parameters were carefully selected to reflect commonly used industrial practices and to ensure repeatability and comparability of the experimental results. The defined machine settings, software tools, and auxiliary materials directly influence stitch accuracy, pattern resolution, and dimensional stability of the QR codes when applied to textile surfaces.

Table 4. Embroidery parameters and material used

Parameter	**Specification**
Embroidery Machine	Ricoma MT-01
Embroidery Software	Wilcom Embroidery
Needles	Organ, DBXK5-NY 80/12
Threads	Madeira Classic No. 40, 100% viscose, Color 1000 (Black), Dtex 135×2
Embroidery Type	Satin stitch
Back Support Material	Non-woven PES interlining, 55 g/m²
Front Support Material	Water soluble PVA film, 35 μm

When considering the embroidery settings and backing materials detailed, it is not possible to embroider 10 mm and 20 mm QR code sizes. The Ricoma MT-01 machine with Madeira Classic No. 40 thread and DBXK5-NY 80/12 needles has a physical stitching limitation, in that the microscopic features of the miniature QR codes cannot be replicated using the minimum stitch length or needle penetration interval. A 10mm or even 20 mm QR-datamatrix code has, on a small space, a lot of individual datamodules which have to be sewn together with sub-millimeter accuracy. With Dtex 135×2 dtex viscose thread and a satin stitch structure, at these dimensions, the width of the thread alone is larger than an individual QR module, leading to merging, lost contrast and distortion of the code. Moreover, the stabilization created by PES interlining and PVA top film is not sufficient at this small scale to counteract the mechanical widening of stitches. Therefore, the embroidery product does not retain the crisp edges and distinct square shapes required for accurate scanning. Consequently, with the given machine, needle, thread count, and stabilizer combination, it is not technically possible to embroider QR codes at 10 mm or 20 mm size.

Two commonly used technologies in the process of printing the polyester-based textile are heat transfer printing and sublimation printing, with both having their own pros and cons depending on the materials, equipment and production needs. The information regarding equipment items and press settings, together with transfer parameters, can be found in Table 5.

Table 5. Heat transfer and sublimation printing parameters

Technology	**Heat Transfer Printing**	**Sublimation Printing**
Machine	Summa Cutters (Plotter, Vinyl, Laser, Flatbed)	Mimaki CJV150-75 (Sublimation Machine)
Transfer Process	350 μm Black Bling Bling Star thermo film, suitable for polyester fabric.	Pigment dye, suitable for polyester
Press	Lotus DEA-25R	Transmatic TS 74M
Pressing Temperature	180 °C	200 °C
Pressing Time	20 seconds	60 seconds

In this application, the heat transfer printing is done through Summa cutting machines, such as plotters, vinyl cutters, lasers, and flatbed machines. It is done with a 350 mm Black Bling Bling Star thermo film, which is a special heat-activated film that is specifically meant to be applied to polyester fabrics. The film is cut into the preferred pattern after which it is placed on the fabric by heat press (Lotus DEA-25R) at 180 °C and 20 seconds. The effect is a raised, textured and visually stimulating surface appearance and is therefore well suited to bold graphics, logos and other decorative features where both tactile and visual effects are essential. Sublimation printing is done on a Mimaki CJV150-75 sublimation printer, which prints the designs with sublimation pigment dyes specially made to print on polyester surfaces. After the design has been printed on sublimation paper, it is transferred onto the textile with the use of a Transmatic TS 74M heat press at 200 °C in 60 seconds. When pressed, the dye becomes gas and permanently bonds to the polyester filaments, creating a bright, permanent and completely integrated print. High-resolution images, gradients, and the all-over design can be printed with sublimation as the print will not be placed above the fabric but instead become a part of the fabric.

3.5. QR Code Readability Assessment Methodology

A controlled smartphone scanning protocol aligned with ISO/IEC 15415 quality principles (lighting, distance control), rather than full laboratory symbol grading. A custom light box was utilized to provide constant and uniform illumination for all imaging procedures. The experimental setup is shown in Figure 8. Two stationary side lighting sources (Numbered: 2) provided constant illuminating conditions and an inspection area (1) to determine a fixed measurement location near the bottom of box was designated to obtain a consistent and repeatable position. The uniform QR code samples were placed at this position. The QR image capturing device (3) was placed at the top of the system and fixed camera-sample distance, 300 mm, simulating real scanning conditions.

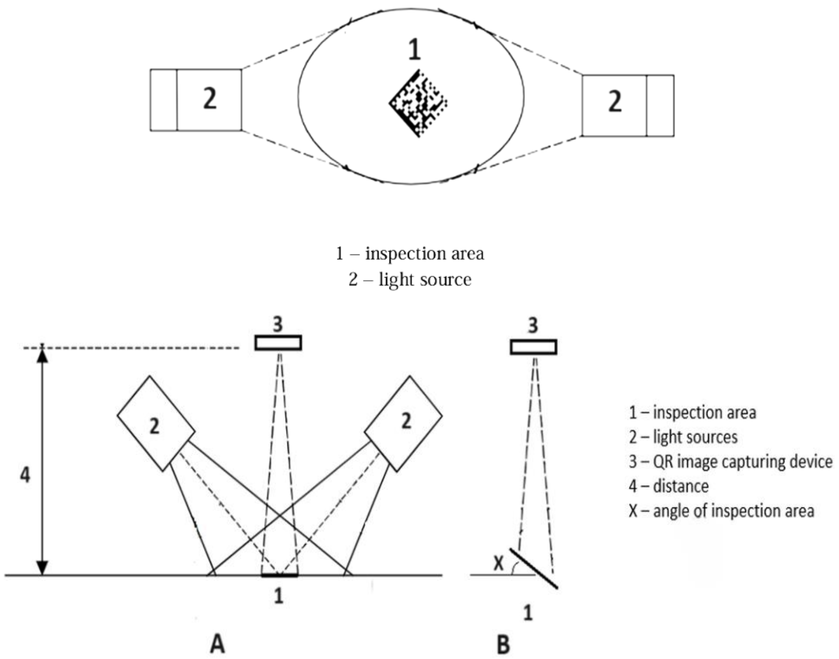


Fig. 8. QR Code Readability Assessment Setup According to ISO/IEC 15415:2011

Every QR code was decoded five times independently. Reads that returned with success in under 3s were awarded a 20% point score, failed attempts a score of 0%, thus leading to an overall readability scoring scheme from zero (“zero” correspondence), up to hundred. A code scanner app (“QR & Barcode Scanner”) obtained from Google Play was installed on a Samsung A53 5G mobile device (user rating 4.5/5) for decoding to guaranty that the scan performance stayed the same in all tests. To assess the effect of physical parameters, we considered QR code dimensions from 10 × 10 mm to 50 × 50 mm. This size is within the range of those most widely applied in textile labels and flexible substrate and offered the possibility to evaluate small and larger format codes under controlled conditions. Two designs models (the original square-module QR codes and the rounded module QR code types) were implemented in order to examine the impact of geometry type on decoding accuracy. Embroidered, sublimated and heat transferred QR codes were tested in order to observe how various application technologies affect module definition, the sharpness of edges and general legibility on deformable textile substrates. This holistic approach provided an extensive analysis the influences of technological, geometric and aspect-related parameters that affect QR code readability on stretchable textile fabrics.

3.6. Methodological Framework for Tensile Testing

The elastic properties of the stretchable fabrics were determined following ISO 20932-1:2018 to assess the influence of deformation on QR code printed or embroidered on these materials. Especially, elastic recovery under multi-cycle loading was quantified to estimate the impact of repeated stretching on QR code reading. Here, elastic recovery refers to the fabric's ability to return to its original dimensions post-stretching and releasing. If the recovery is incomplete, it causes permanent deformation that may slightly shift or misalign the QR code modules (marks). Such geometrical discrepancies may reduce the fidelity of contrast and position required by imaging systems making the QR code less likely to be reliably detected and decoded by scanners.

3.6.1. Sample Preparation

In this research, the durability and readability of QR codes applied to stretchable knitted fabrics were investigated using the ISO 20932-1:2018 strip test method. For this method, the fabric was cut to specimens in stripe form with 250 mm in length and 50 mm in width. The strips were made in both warp and weft. In the case of knitted fabrics, these are the directions wale and course (in this paper referred to as vertical (V) and horizontal (H).

Five dimensions of QR codes side lengths were approximately 10 mm, 20 mm, 30 mm, 40 mm and 50 mm were applied for this experiment. Three different methods for applying the QR codes on to the fabric were used for each size in order to allow a comparison of their performance: heat transfer printing (T), sublimation printing (S), and embroidery (E).

Fig. 9. Prepared samples for the experiment

A simple code system was assigned to all samples. For instance, for the sequence 3T1-H

1) The first number (3) shows the QR code size in centimetres (3 cm = 30 mm),
2) The letter (T, S or E) shows the application technique (T-heat transfer, S-sublimation, E-embroidery),
3) The next number (1, 2, …) is the specimen number for that combination, and
4) The last letter shows the direction of the strip (H-horizontal, V-vertical)

Based on this encoding scheme, samples denoted 3T1-H, 3T1-V (for the QR code of a size of mm), and similar codes for the other four sizes (10, 20, 40 and 50 mm). A total number of 66 (3 sample per test and mean value will be consider) samples were studied (5 QR code sizes, 3 application methods and 2 fabric orientations) and calculated mean value and statical reliability.

3.6.2. Test Procedures

In this study, sublimation QR codes were tested in all five sizes (10, 20, 30, 40, and 50 mm). In contrast, heat transfer and embroidery were evaluated only for the larger sizes 30, 40, and 50 mm, because the 10 mm and 20 mm versions were not included in the experimental set. Therefore, the results in the following section are reported only for the size technique combinations that were actually tested. Elastic properties of the knitted fabric were evaluated in accordance with ISO 20932-1:2018 [21]. This standard gives a set of unified methods to measure the stretch and recovery behaviour of textile fabrics under cyclic tension is especially suitable for knitted materials because their looped structure allows large and mostly elastic extensions. The test aimed to characterize how the fabric behaves during repeated stretching and relaxation, and to quantify properties such as elastic recovery and permanent set after cyclic loading. Testing was performed using a Tinius Olsen universal testing machine equipped with manual flat-faced grips.

Fig. 10. Tinius Olsen Universal Testing Machine

These grips were used to hold the specimens firmly and to minimise slippage during the test. The gauge length (distance between grips) was fixed at 100 mm, as recommended by the standard for knitted fabrics. All tests were carried out in a controlled laboratory environment.

Table 6. Test parameters for elastic properties according to ISO 20932-1:2018

Parameter	**Value**
Fabric type	Knitted fabric
Gauge length	100 mm (fixed)
Number of cycles	5 cycles
Grip type	Manual flat-faced grips
Extension rate	500 mm/min
Maximum extension	50% (extended from 100 mm to 150 mm)
Preload	0.5 N
Specimen orientation	Course and wale directions

Rectangular specimens were cut so that tests could be carried out both in the course direction (horizontal loops) and in the wale direction (vertical loops). Each specimen was mounted between the grips of the testing machine and aligned so that the direction of stretching matched the selected fabric direction. The gauge length was adjusted to 100 mm before starting the test. A preload of 0.5 N was first applied. This small initial force removed slack, straightened the specimen, and ensured that the starting length was well defined. After the preload was reached, the crosshead was driven at a constant speed of 500 mm/min until the specimen length reached 150 mm, corresponding to 50% extension relative to the initial gauge length.

Once the maximum extension of 50% was reached, the crosshead was moved back to the preload position (0.5 N), allowing the specimen to contract. This loading-unloading sequence was defined as one cycle. The same cycle was then repeated until a total of five cycles had been completed for each specimen. The machine continuously recorded the force and extension during all cycles. At the end of the fifth cycle, while the specimen was again at the preload condition, the residual length was measured. This value was used to calculate the permanent set and to evaluate the fabric's ability to recover its original length after repeated stretching. For each specimen, the tensile test measured the residual force and the maximum load in the first cycle (Max C1) and in the fifth cycle (Max C5), together with their stresses. Residual force was the force needed to stretch the sample to a fixed elongation after the first loading. Max C1 and Max C5 were the highest forces recorded in the first and fifth loading cycles, respectively. These values were then used to analyse how the knitted fabric stretches and recovers under repeated loading.Permanent deformation is the extension that a specimen shows after being stressed, and then unloaded with stress removed for a period of time to let it recover. For this test, each specimen has an initial gauge length of 100 mm. After loading and unloading, the ultimate length is measured 30 minutes later to release any relaxed material. The difference between the initial 100 mm and the length after 30 minutes is the permanent deformation. A greater difference represents more loss in the structure and less elastic property of the material to return to its original form.

3.6.3. Calculation of Tensile Parameters

Force Decay (B): shows how much the material loses strength after it has been stretched once and then loaded again. To find this value, the maximum force from the first cycle (X) is compared with the maximum force from a later cycle (Y). The calculation is:

$$B = \frac{X-Y}{X} \times 100 \qquad (8)$$

here, **X** is the maximum force in the first cycle and **Y** is the maximum force in the later cycle at the same elongation. A higher B value means the material becomes softer after repeated loading.

Permanent Deformation (C): tells us how much length the specimen does not recover after the load is removed. In this test, each sample starts with an initial gauge length of 100 mm. After stretching and releasing, the length is measured again after 30 minutes. The difference between the two lengths shows how much the material has permanently changed. The formula is:

$$C = \frac{Q-P}{P} \times 100 \qquad (9)$$

Where P is the initial 100 mm, and Q is the length measured after 30 minutes. A higher C value means the specimen keeps more permanent stretch.

Recovered Elongation (D): shows how much of the original length the material can return to after being stretched. It is calculated as:

$$D = 100 - C \qquad (10)$$

here, **C** is the permanent deformation. A higher D value means the material was recovered more effectively after the test.

3.7. Determination of Fabric Thickness

The thickness of each fabric sample was determined using a J-40-T thickness gauge in accordance with DIN EN ISO 5084[33]. During all measurements, the instrument applied a constant pressure of 1.0 kPa over a contact area of 2 cm².

Fig. 11. J-40-T promoter

Prior to each measurement, the sample was laid flat under the measuring foot and gently smoothed out to eliminate creases or folds. The gauge was then placed on the fabric, and the thickness was measured after an initial reading stabilisation. This approach provides a standardised compression of the sample and the same measurement conditions without distorting. Consequently, the measured thickness values describe the true structural condition of fabrics and can be compared with other experiences using the same DIN EN technology.

3.8. Domestic Wash Methodology

The domestic washing procedure was carried out according to ISO 6330:2012. All specimens were washed and dried using an automatic washing machine and dryer (Samsung F2J6HM0W). The washing setting selected was Normal, which is recommended for synthetic fibres such as polyester.

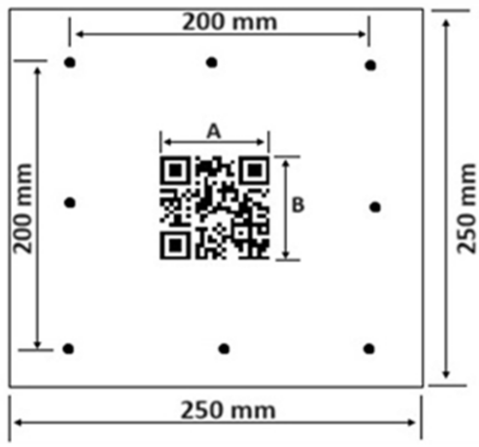


Fig. 12. Specimen scheme for wash procedure

The washing temperature was maintained at 40°C, with a 1000 r/min drum speed. One complete washing cycle consisted of 2 hours of washing followed by 1 hour of tumble drying. Each specimen underwent a total of five wash and dry cycles. After every cycle, two main parameters were evaluated:

1. Mass loss,
2. Shrinkage of the specimen.

The test specimens used for washing were prepared at a fixed size of 250 mm × 250 mm. To measure shrinkage, reference points were marked on each specimen in three different positions along both width and length. The distance between each pair of reference marks was 200 mm, as illustrated in the specimen layout. Additionally, the QR code printed on each sample was measured in two directions (A and B) before and after the five cycles to assess dimensional stability.

3.9. Image Analysis of QR Codes

The visual changes of the QR codes before and after tensile testing were evaluated using ImageJ software (National Institutes of Health, USA). All QR code images were acquired with an Epson Perfection V370 Photo flatbed scanner. Each sample was put face down on the glass of the scanning device and adjusted to a fixed area corner location, ensuring that the product QR code was in an identical position and orientation pre- versus post-measurement. The scanner was used in a reflection mode and with an optical resolution fixed (which was maintained constant for each of the samples).
Images were saved as uncompressed TIFFs and converted to 8-bit greyscale to prevent artefacts of compression and to normalize the image data for analysis.

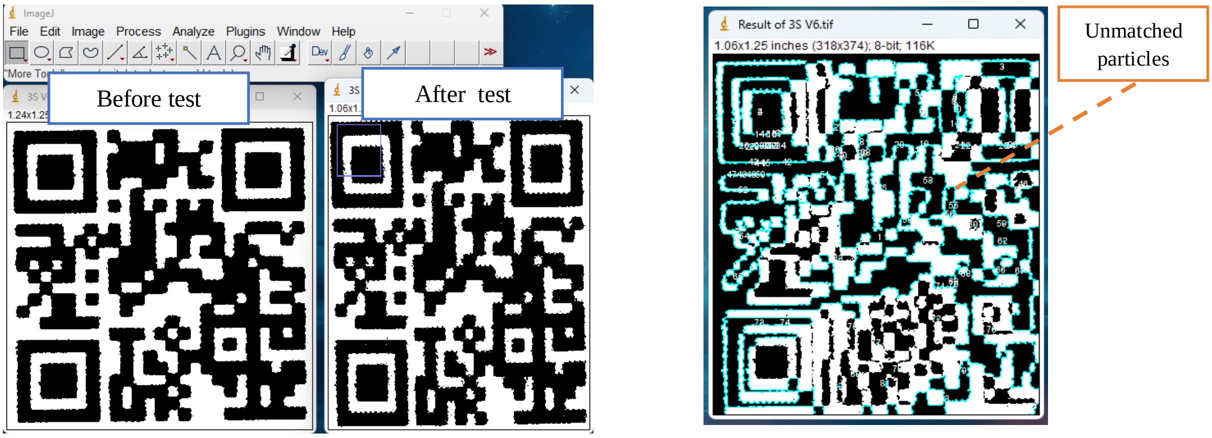


Fig. 13. QR code image analysis using ImageJ

The QR code region of each sample was cropped to a region of interest with only the code and small background margin. The greyscale images were then turned into binary (black–white) ones by using the threshold function in ImageJ, assuming the darker QR modules to be "particles". The number of particles and total area per QR code image were measured using Analyze Particles.

The particle information of the specimens before and after tensile testing were compared next. For each pair of specimens, the differences in particle count and particle area (in absolute values as well as in percent) were determined. These variations were considered as distortion in the QR pattern due to fabric deformation, which was later correlated with the performance of QR code readability.

4. Results and Analysis

This chapter reports experimental results on the durability and scan reliability of QR codes when printed on a stretchable polyester–spandex interlock fabric. The experiment is based on a factorial design with the following options: five QR sizes (10, 20, 30, 40 and 50 mm), three application methods (heat transfer, sublimation and embroidery), with two fabric orientation alternatives (horizontal/course and vertical/wale). The findings are presented in four main sections: (i) mechanical response during multi-cycle tensile loading, with post-tensile thickness measurements to record any compression or structural behavior; (ii) wash durability after five wet–dry cycles; (iii) QR code readability taken at each interval condition (baseline, post-tensile and washing), to observe variations in scan quality; and, finally (iv) image-based analysis using ImageJ particle metrics is used to quantify structural pattern change within the QR images pre- and post-tensile exposure.

4.1. Tensile Test Results

Tensile test (multi-cycle loading) was conducted to study the mechanical performance of the stretchable polyester interlock fabric under multiple stretching and recovery process. The findings are presented using maximum forces during Cycle 1 (Max C1) and Cycle 5 (Max C5), as well as force decay (B), residual deformation (C) and recovered elongation (D). Peak force both decreased from the first to the fifth cycle, suggesting that the fabric had experienced mechanical conditioning under repeated loading. Permanent set and recovered elongations specify the amount of residual set and recovery following unloading. Furthermore, the fabric thickness was measured post-tensile cycling to account for whether any compaction or rearrangement had resulted from repeated loading**.**

Table 7. Multi-Cycle Tensile Test Data

Tensile test data							
Specimen No	**Sample code**	**Residual 1 %**	**Max. C1, N**	**Max. C1, Mpa**	**Residual 5%**	**Max. C5, N**	**Max. C5, Mpa**
1	1S H	4.875	17.82	0.0036	7.88	16.66	0.0033
2	1S V	25.16	248.6	0.0497	28.95	219.2	0.0438
3	2S H	7.28	19.67	0.0039	8.3	17.54	0.0035
4	2S V	21.15	211	0.0422	28.2	186.5	0.0037
5	3S H	7.2	23.22	0.0046	8.58	19.82	0.0339
6	3S V	23.55	230.5	0.0461	26.4	207	0.0411
7	4S H	5.1	23.01	0.0046	8.18	20.83	0.0042
8	4S V	22.48	227.1	0.0454	26.4	198.8	0.0398
9	5S H	7.85	20.93	0.0042	8.95	19	0.0038
10	5S V	23.25	229.8	0.046	26.65	203.4	0.0407
11	3T H	10.2	28.31	0.0057	13.33	23.45	0.0047
12	3T V	23.25	229.3	0.0459	27.08	211.8	0.0424
13	4T H	6.83	30.36	0.0061	10.43	26.2	0.0051
14	4T V	22.88	214.4	0.0429	26.63	192.4	0.0385

Tensile test data							
Specimen No	**Sample code**	**Residual 1 %**	**Max. C1, N**	**Max. C1, Mpa**	**Residual 5%**	**Max. C5, N**	**Max. C5, Mpa**
15	5T H	9.38	39.7	0.0079	12.3	32.02	0.0064
16	5T V	21.58	229	0.0458	26.38	197.4	0.0395
17	3E H	12.43	51.9	0.0104	16.28	41.49	0.0083
18	3E V	24.75	245.6	0.0491	27.48	215.9	0.0432
19	4E H	12.13	83.1	0.0166	19.48	64.9	0.013
20	4E V	26.55	239.8	0.048	29.38	208	0.0416
21	5E H	19.68	134.8	0.027	24.73	67.7	0.0135
22	5E V	26.18	221.5	0.0443	29.78	184.5	0.0369

Table 8. Recovery Length Data After Tensile Cycling

Specimen No	**Sample code**	**P: Initial gauge length (in mm)**	**Q: Length after recovery (in mm)**
1	1S H	100	100
2	1S V	100	104
3	2S H	100	100
4	2S V	100	105
5	3S H	100	100
6	3S V	100	106
7	4S H	100	101
8	4S V	100	108
9	5S H	100	101
10	5S V	100	108
11	3T H	100	100
12	3T V	100	105
13	4T H	100	101
14	4T V	100	107
15	5T H	100	103
16	5T V	100	108
17	3E H	100	104
18	3E V	100	110
19	4E H	100	103
20	4E V	100	106
21	5E H	100	106
22	5E V	100	110

The tensile data exhibit a marked anisotropy. The fabric had considerably higher load capacity in the vertical (V/wale) than the horizontal (H/course) direction (average Max C1/Max C5 ≈ 229.7/202.3 N in V versus 43.0/31.8 N in H). Peak force decreased on both sides from Cycle 1 to Cycle 5, denoting mechanical adaptation, where a larger average decrease was observed on H (17.5%) compared to V (11.9%). The residual strain increased after cycling from 9.36% - 12.59% in H and 23.71% - 27.58% in V, indicating higher permanent set into the vertical direction.

Recovered elongation was determined using the specimen length measured 30 minutes after unloading. Each sample had an initial gauge length of P = 100 mm, and the length after recovery (Q) was recorded after 30 minutes while the specimen was kept relaxed and free of any load Force decay, permanent deformation, and recovered elongation were obtained from the tensile test results as well as the measurements at 30-minute recovery (Table 7 and Table 8) using Equations (8–10). The force decay (B) reflects the extent to which the peak force decreases during repeated loading and was calculated as that of first cycle (X = Max C1) relative to other cycles at the same elongation (%), B = X − Y)/X × 100 (Equation_GAIN). 8). The permanent deformation in the 5th cycle (C) was calculated from the initial gauge.P length (P = 100 mm) and length of specimen measured after recovery for 30 minutes (Q) C = Q −P= /P100% Eq. 9). The percentage elongation to recovery (D) then calculated as D = 100 − C (Eq. 10). Therefore, higher D values mean a better recovery but the higher C values mean more remnants after tensile loading.

Table 9. Tensile Results and QR Code Readability (Before and After)

Specimen number	**Specimen code**	**Force decay due to exercising B**	**Permanent deformation % 5th cycle C**	**Recovered Elongation *D***	**QR code readability %**	
					Before test	**After test**
1	1S H	6.51%	0%	100%	0%	0%
2	1S V	11.83%	4%	96%	0%	0%
3	2S H	10.83%	0%	100%	100%	100%
4	2S V	11.61%	5%	95%	100%	100%
5	3S H	14.64%	0%	100%	100%	100%
6	3S V	10.20%	6%	94%	100%	100%
7	4S H	9.47%	1%	99%	100%	100%
8	4S V	12.46%	8%	92%	100%	100%
9	5S H	9.22%	1%	99%	100%	100%
10	5S V	11.49%	8%	92%	100%	100%
11	3T H	17.17%	0%	100%	100%	100%
12	3T V	7.63%	5%	95%	100%	100%
13	4T H	13.70%	1%	99%	100%	100%
14	4T V	10.26%	7%	93%	100%	100%
15	5T H	19.35%	3%	97%	100%	100%
16	5T V	13.80%	8%	92%	100%	100%

Specimen number	Specimen code	Force decay due to exercising B	Permanent deformation % 5th cycle C	Recovered Elongation *D*	QR code readability %	
					Before test	After test
17	3E H	20.06%	4%	96%	0%	0%
18	3E V	12.09%	10%	90%	0%	0%
19	4E H	21.90%	3%	97%	40%	0%
20	4E V	13.26%	6%	94%	40%	0%
21	5E H	49.78%	6%	94%	20%	0%
22	5E V	16.70%	10%	90%	20%	0%

The 10 mm QR code dimension could not able to be provided for all application types. As the QR-code is a square with 25×25 elements this results in an element size of some 0.4 mm (10/25), which is standing below the current practical production resolution and handling capability of our sourcing and producing sources. Therefore, heat transfer and embro idery at 10 mm could not be realized and tested, calculating the dimensional size of 10 mm only applied to the manufacturing method sublimation being able to do with reliability.

4.1.1. Sublimation (S)

Sublimation demonstrated a reliable mechanical response through cyclic tensile loading for mild force drop (mean B = 10.83% (range, 6.51–14.64%), n = 10). The recovery was direction-dependent: the horizontals (H) had much reduced permanent deformation (C mean = 0.40%) and almost complete recovery (Dmean = 99.60%), whereas the verticals (V) exhibited considerably more residual set (C mean=6.20%) and lower recovery levels D mean=93.80%). The overall recovery was high (range of D, 92–100%).This confirmed good elastic return after the 30-minute rest period.

4.1.2. Heat Transfer (T)

Heat transfer showed the most optimal mechanical stability within the tested range, regarding controlled softening (average B = 13.65%, range 7.63–19.35%, n = 6) and high recovery after 30 minutes (total D mean = 96.0%, range 92–100%). Except H (C mean = 1.33%) and V samples (C mean =6.67%), where recovered elongations formed D mean =93.33%. This demonstrates that directionality of the knit formation is still the principal cause of residual set even if the application technique is mechanically constant.

4.1.3. Embroidery (E)

Embroidery revealed the worst situation in tensile cycling with least level and most variable of force decay (mean B = 22.30%, range 12.09–49.78% n = 6) with an extreme value at 50 mm on H (B = 49.78%). Permanent deformation also surpassed those for the printed techniques, mainly in the vertical sense (C mean = 8.67% vs 4.33% on H), yielding the smallest recovery elongation of all three (D mean = 93.5%, with minima of 90%). These findings, point towards a more severe disruption in mechanics and lesser dimensional recovery of embroidery under repeated tensile.

4.1.4. Analysis of QR Readability Before and After Tensile Test

A strong dependence of the application method and the QR size is observed when subjected to tensile cycling. Concerning sublimation, size dependency of the readability is illustrated well in the smallest condition that 10 mm code is unreadable both before and after tensile loading (0% → 0%). However, at the size of 20 mm and above there is stabilisation in sublimation which being 100% before and after tensile exposure (100% → 100% for 20–50 mm). It follows that tensile cycling does not compromise the integrity of sublimated codes (provided that a minimum physical size is exceeded).In terms of heat transfer, all the sizes tested (30–50 mm) are read entirely before and after tensile loading (100% → 100%). This indicates the optimal functional stability over the examined range and that the heat transfer application serves to partially stabilize a pattern under cyclic stretching. (Heat transfer characteristics of 10 mm was not available due to manufacturing limitations and hence no inference can be made for 10 mm).

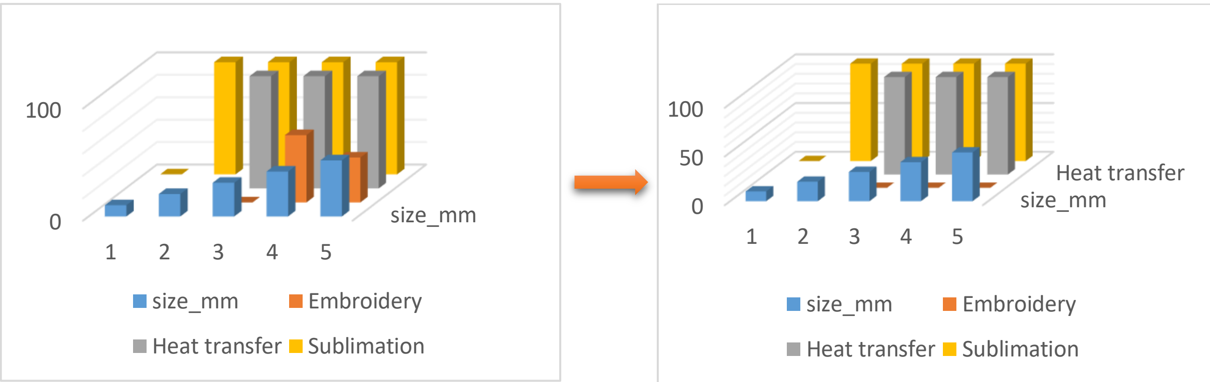


Fig. 14. Graphical illustration of QR code readability before and after tensile cycling: a - Readability before tensile (%), b - Readability after tensile (%)

Meanwhile, tensile stability of embroidery is the lowest. With 30 mm, codes are unreadable at baseline (0 %) and after tensile. At 40–50 mm, embroidery partially displays line readability (60% at 40 mm and 40% at 50 mm), whereas tensile visualizes no readability with both thicknesses as compared to baseline (60% → 0% and 40% → 0%). This implies that the actual distortion of the embroidered module geometry due to cyclic stretching is high enough to prevent functional scanning, even if initial readability is good.In general, the results support a practical minimum size threshold of ≥20 mm for sublimation and successful heat transfer (30–50 mm tested) as the most robust method under tensile cycling with embroidery being unable to maintain QR readability after tensile exposure on this stretchable knit substrate.

4.1.5. Observation on Suitable QR technique and Size for Stretchable Textile Material

From the tensile-stage (B, C, D) results of mechanical property and corresponding readability results, it was found that the optimal tends to be heat transfer when both methods apply to such stretchable fabric of polyester interlock, with the exception of a minimum size for QR code. Heat transfer had the best durability, most significantly in the range tested and suggested for 30–50 mm it holds stable properties after tensile cycling, returning high recovery despite retaining a greater residual set in vertical.

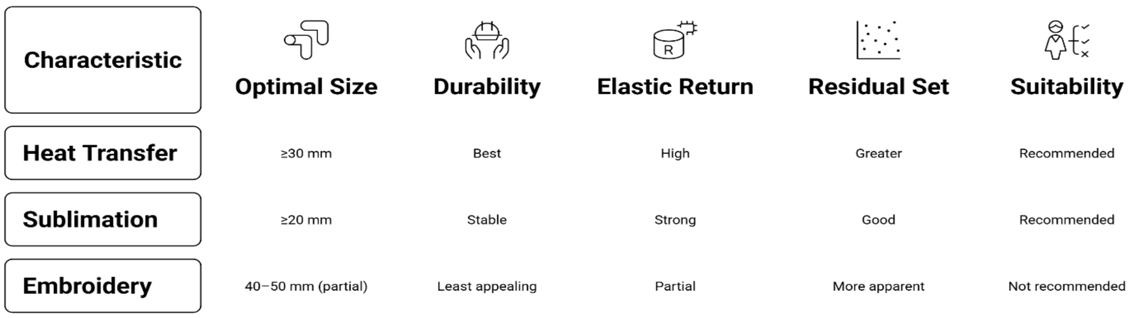


Fig. 15. Illustration of QR Code Performance on Stretchable Fabric by Application Method

Sublimation is applicable for 20–50 mm, conditions where it was stable after tensile exposure and performed with a generally strong elastic return, unlike the case of 10 mm, which was not suitable in this system as the effective module dimension (~0.4mm/module for a 25×25 symbol) went well below practical textile-resolution limits and failed during end-use testing. For stretchable textiles in this application however, embroidery is not the technology of choice: while even the bigger sizes obtained some (partial) baseline performance (40–50 mm), tensile cycling erased functional performance and embroidery was as well alongside thermo-transfers by far the less appealing regarding mechanical stability (more apparent force decay, more apparent residual deformation especially in vertical direction). In general, we recommend heat transfer at ≥30 mm and sublimation at ≥20 mm for a printing process that can be reliably applied to stretchable knitted substrates, and that embroidery should not be used for QR codes required to endure repeated stretching while still being functional.

4.2. Thickness Measurement Results

Thickness variation after tensile loading had a marked and uniform directionality depending on the application mode, with the vertical (V/wale) orientation yielding consistently greater thickness increases than horizontal (H/course), pointing to anisotropic out-of-plane recovery of the knitted layer. For sublimation, thickness increased from of 22.22–51.43% in H and 45.00–74.29% in V, producing significantly more post-tensile structural expansion in the wale axis than the course direction.

Table 10. Thickness Before and After Tensile Test and Thickness Change

Specimen No	Sample code	Thickness before test (mm)	Thickness after test (mm)	Thickness change(%)
1	1S H	0.35	0.48	37.14%
2	1S V	0.35	0.56	60.00%
3	2S H	0.35	0.53	51.43%
4	2S V	0.35	0.61	74.29%
5	3S H	0.35	0.53	51.43%
6	3S V	0.35	0.58	65.71%
7	4S H	0.35	0.45	28.57%
8	4S V	0.39	0.58	48.72%
9	5S H	0.36	0.44	22.22%

Specimen No	Sample code	Thickness before test (mm)	Thickness after test (mm)	Thickness change(%)
10	5S V	0.4	0.58	45.00%
11	3T H	0.43	0.55	27.91%
12	3T V	0.43	0.63	46.51%
13	4T H	0.43	0.55	27.91%
14	4T V	0.43	0.66	53.49%
15	5T H	0.43	0.55	27.91%
16	5T V	0.43	0.68	58.14%
17	3E H	1.85	2.06	11.35%
18	3E V	1.68	2.21	31.55%
19	4E H	1.7	2.16	27.06%
20	4E V	1.68	2.28	35.71%
21	5E H	1.82	2.32	27.47%
22	5E V	1.72	2.45	42.44%

For heat transfer, the thickness for horizontal specimens increased uniformly (27.91%) as opposed to vertical specimens (46.51–58.14% thicker), indicating that the anisotropic mechanics govern theresponse in thickness rather than by the surface-applied layer.

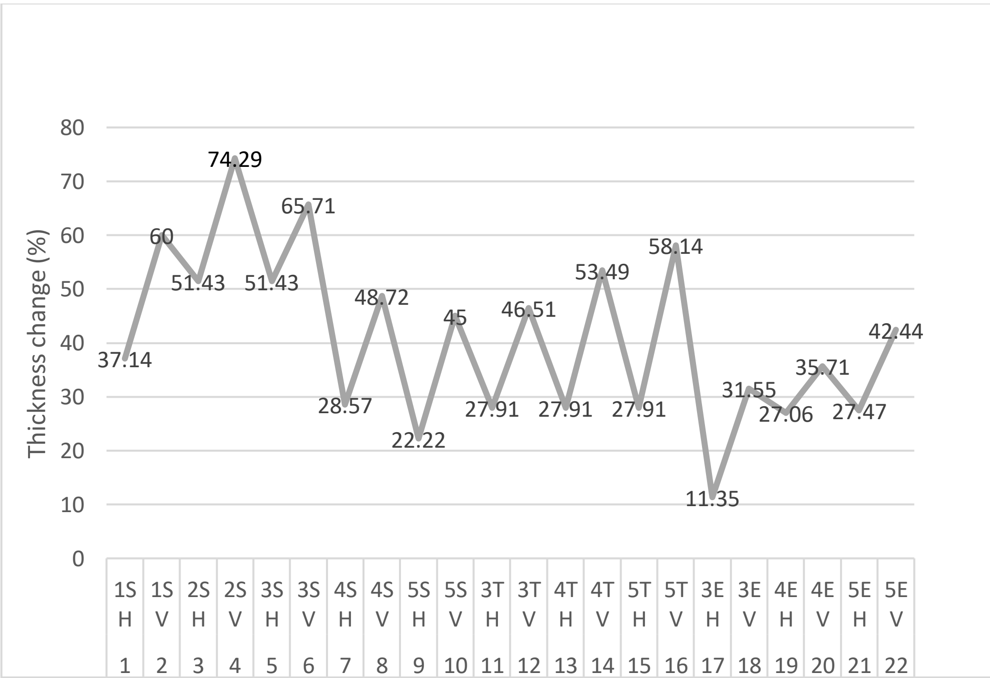


Fig. 16. Graphical illustration of thickness change (%) after tensile test

Regarding embroidery, the trend was also observed despite initial thicker structures because of stitching and fabric backing: H (11.35–27.47%) and V (31.55–42.44%), indicating region-specific out-of-plane thickening under cyclic load (f). Generally, the dimension in the vertical direction experienced a high degree of thickness increase that ranged from 15 to 25% more compared to the horizontal one for all three methods, indicating that fabric orientation is the primary reason behind post-tensile change in thickness and the technique used only affects its magnitude.

4.3. Wash Durability Results to Estimate Fabric Shrinkage and QR Readability Before and After Five Wash-Dry Cycles

Testing domestic washing conditions (ISO 6330:2012) was applied to approximate the effect of functioning on garment specimen integrity and QR operability during laundering. At the end of each wash-dry cycle, mass loss and dimension shrinkage were measured to quantify material degradation and structural relaxation. Furthermore, QR code stability was tested, determining the printed code size in two orthogonal directions (A and B) before and after a five-cycle sequence. QR reading was evaluated and compared at each modification step in order to identify whether or not changes in fabric size and code geometry were also reflected in the overall reduction of scanning reliability. This dual approach connects physical durability (mass and shrinkage) to functional performance (QR readability) under real-life home care conditions.

Table 11. Effect of Laundry on Fabric Dimensions and QR Code Size (H-Horizontal, V-Vertical)

Sample	Fabric Shrinkage H (%)	Fabric Shrinkage V (%)	QR Size Before (mm)	QR After H (mm)	QR Shrinkage H (%)	QR After V (mm)	QR Shrinkage V (%)
1S-7	1.3	2.7	10	9.5	5.0	9.5	5.0
1S-8	1.2	3.2	10	10.0	0.0	9.5	5.0
1S-9	1.2	3.3	10	10.0	0.0	10.0	0.0
2S-7	2.2	3.2	20	20.0	0.0	19.0	5.0
2S-8	1.6	3.3	20	20.0	0.0	19.5	2.5
2S-9	1.5	2.2	20	19.5	2.5	19.5	2.5
3S-21	2.3	2.7	30	29.5	1.7	29.5	1.7
3S-22	2.0	2.7	30	29.0	3.3	29.5	1.7
3S-23	1.2	1.2	30	29.0	3.3	29.5	1.7
4S-11	1.7	1.5	40	39.0	2.5	39.5	1.3
4S-12	2.0	1.3	40	39.0	2.5	39.0	2.5
4S-20	1.7	2.0	40	39.0	2.5	39.0	2.5
5S-18	1.7	1.7	50	48.5	3.0	49.0	2.0
5S-19	2.3	2.2	50	48.0	4.0	49.0	2.0
5S-20	2.0	1.2	50	48.5	3.0	49.0	2.0
3T-14	1.7	2.2	30	29.0	3.3	29.0	3.3
3T-15	1.8	1.7	30	29.0	3.3	29.0	3.3
3T-18	1.5	1.8	30	29.0	3.3	29.5	1.7
4T-14	2.0	2.3	40	38.5	3.8	38.5	3.8
4T-15	1.8	2.5	40	39.0	2.5	38.5	3.8
4T-18	2.0	1.5	40	39.0	2.5	39.0	2.5
5T-14	1.8	2.3	50	47.5	5.0	49.0	2.0
5T-15	1.5	1.8	50	48.0	4.0	48.5	3.0
5T-16	1.8	2.3	50	48.0	4.0	48.0	4.0
3E-17	2.2	2.8	30	28.0	6.7	30.0	0.0
3E-18	2.3	2.0	30	28.0	6.7	30.0	0.0
3E-19	1.5	3.2	30	28.5	6.3	30.0	0.0
4E-16	2.0	2.3	40	37.0	7.5	40.0	0.0
4E-17	1.5	1.8	40	37.5	6.3	40.0	0.0

Sample	Fabric Shrinkage H (%)	Fabric Shrinkage V (%)	QR Size Before (mm)	QR After H (mm)	QR Shrinkage H (%)	QR After V (mm)	QR Shrinkage V (%)
4E-19	2.2	2.5	40	37.0	7.5	40.0	0.0
5E-16	2.2	2.2	50	45.0	10.0	50.0	0.0
5E-17	2.3	2.2	50	45.0	10.0	49.5	1.0
5E-18	1.5	2.2	50	45.0	10.0	49.5	1.0

Shrinkage seems to be quite moderate between measurements (in the fabric). It is 1.2–2.3% in the H plane and 1.2–3.3% in the V plane, while the average in H and V is 1.79% and 2.39%, respectively. In contrast, QR shrinkage varies to a larger extent, between 0 and ±10% in H and V, with global average values of 4.75% (H) and 1.78% (V). This shows that the variations of QR size are not due to fabric shrinkage only. The offset due to the labeling adds further distortion, in some cases even more than the fabric shrinkage relative to QR.

4.3.1. Sublimation (S)

QR tends to be low. Average QR shrinkage across the sublimation set is 1.94% in H and 2.58% in V; however, at 20–30 mm these parameter changes are close to zero (on average approximately 1.80% in H and 2.52% in V). Some even reach 0%, indicating that after washing the geometry of the QR can be almost maintained unchanged. Nevertheless, it can be observed that the 10 mm QR codes are distributed over a larger area, and they also shrink up to 5%, which implies that because of the small size they become more sensitive to washing-related changes, causing easier loss of dimensional stability.

4.3.2. Heat Transfer(T)

The level of shrinkage is moderate and rather uniform. Average shrinkage is 3.85% in H and 3.10% in V. In fact, the 30 mm samples exhibit a consistent pattern of around 3.3% shrinking in either direction, while the dimensions for the larger (40–50 mm) specimens fall towards values between 3.8–5.0% in H (2.0–3.8% in V). This is indicative of reproducible contraction, presumably not only governing fabric migration but also involving issues related to mobility driven by the transfer layer and adhesive interface behaviours, as measured locally.

4.3.3. Embroidery(E)

The distortion is obviously unidirectional and more pronounced. Horizontal QR shrinkage is large (average 8.58%, range between 6.3% and 10.0%), while vertical shrinkage remains mostly close to zero (average 0.22%, range from 0% to 1.0%). This would indicate that stitch tension and structural pull deform the QR primarily along one axis, as the QR can be compressed significantly while fabric shrinkage remains at some 2–3%.

Table 12. QR Code Readability Before and After Washing Test ISO 6330-2012

Sample	Tech	Readability Before (%)	Readability After (%)	Change (After−Before)	Status
1S-7	S	0	0	0	No change
1S-8	S	0	0	0	No change
1S-9	S	0	0	0	No change
2S-7	S	100	100	0	No change
2S-8	S	100	100	0	No change

Sample	Tech	Readability Before (%)	Readability After (%)	Change (After−Before)	Status
2S-9	S	100	100	0	No change
3S-21	S	100	100	0	No change
3S-22	S	100	100	0	No change
3S-23	S	100	100	0	No change
4S-11	S	100	100	0	No change
4S-12	S	100	100	0	No change
4S-20	S	100	100	0	No change
5S-18	S	100	100	0	No change
5S-19	S	100	100	0	No change
5S-20	S	100	100	0	No change
3T-14	T	100	100	0	No change
3T-15	T	100	100	0	No change
3T-18	T	100	100	0	No change
4T-14	T	100	100	0	No change
4T-15	T	100	100	0	No change
4T-18	T	100	100	0	No change
5T-14	T	100	100	0	No change
5T-15	T	100	100	0	No change
5T-16	T	100	100	0	No change
3E-17	E	0	0	0	No change
3E-18	E	0	0	0	No change
3E-19	E	0	0	0	No change
4E-16	E	0	0	0	No change
4E-17	E	0	0	0	No change
4E-19	E	40	0	-40	Decrease
5E-16	E	20	0	-20	Decrease
5E-17	E	20	0	-20	Decrease
5E-18	E	0	0	0	No change

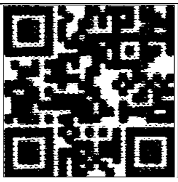
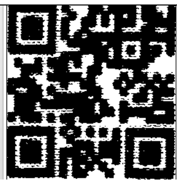
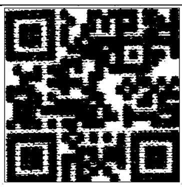
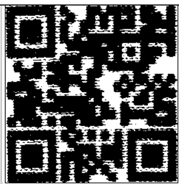
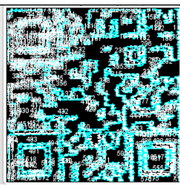
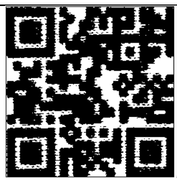
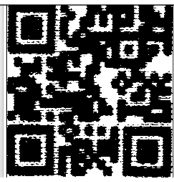
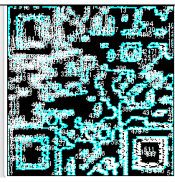
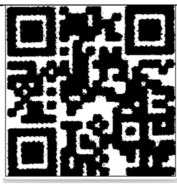
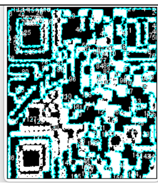
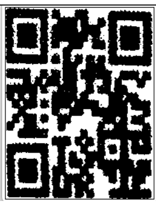
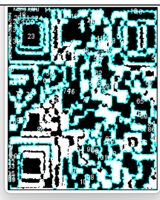
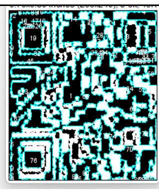
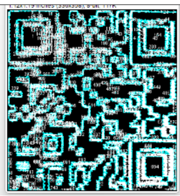
For all washed samples (n = 33), QR readability was mostly consistent pre and post wash. Twenty-one samples (63.6%) were still all readable (100% - 100%) while nine samples (27.3%) were still unreadable at 0% - 0%. Only three samples (9.1%) were affected by washing, all of them being embroidery cases that pass from partial to unreadable and show the same pattern of drop (4E-19: 40% - 0%; 5E-16: 20% - 0%; 5E-17: 20% - 0%).

According to the technology, a (sublimation revealed an obvious size limitation: 10 mm codes were unreadable (0% - 0%) and ≥20 mm codes reading was unaffected (100% - 100%). Heat transfer remained completely readable at all sizes tested (100% - 100%). Embroidery scored the lowest, as most samples were illegible already at baseline and for those that could be partially read, they became unreadable after washing.

4.4. Results Analysis of Image-based Geometric Change after Tensile Testing

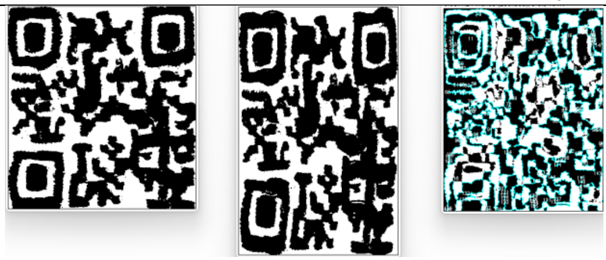
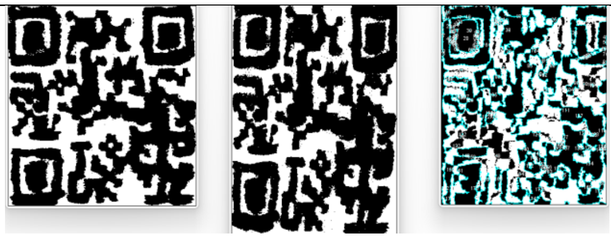
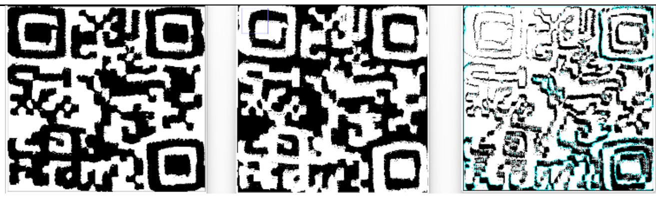
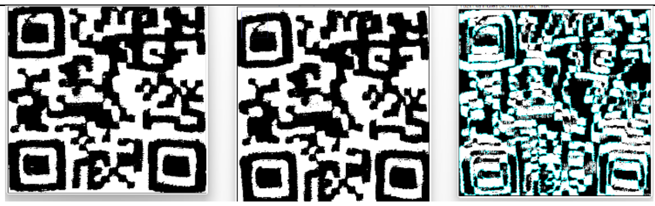
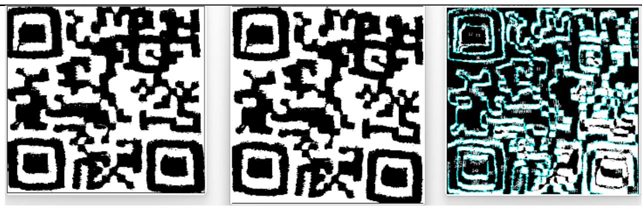
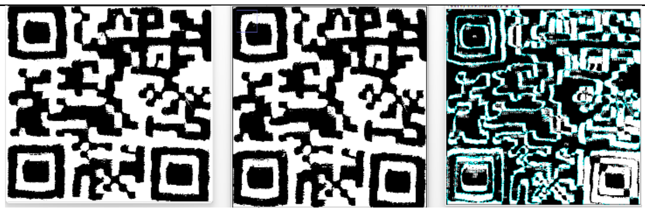
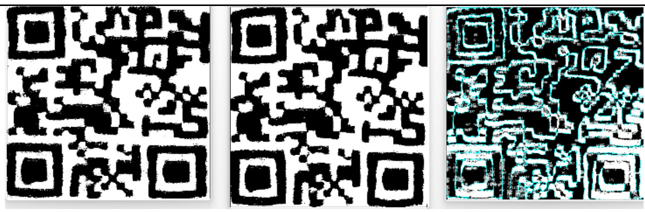
The scanned QR images before and after tensile cycling were analyzed using ImageJ to measure pattern distortion. Displacement of both particle counts and particle area 29 measures of the binarized QR region suggest that a module has fractured or amalgamated and that the boundaries between modules have been deformed. In general, higher deviations are anticipated in the V/wale direction because of higher residual set and more stable methods (typically sublimation/heat transfer at large size) cause smaller metric changes than methods that are structurally discontinuous, like embroidery.

Table 13. Image analysis tensile tested specimen

SPECIMEN	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
2S H1				336	0.156	25.284
2S H2				579	0.134	22.098
2S H3				548	0.119	19.651
2S V4				157	0.232	42.197
2S V5				109	0.236	43.157
2S V6.tif				89	0.23	41.286
3S H31.tif				445	0.318	23.364
3S H32.tif				764	0.321	24.03
3S V11.tif				161	0.587	47.061

SPECIMEN	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
3S V12.tif				115	0.547	45.21
4S H1.tif				594	0.4	16.647
4S H2.tif				489	0.435	18.051
4S H3.tif				454	0.586	24.474
4S V14.tif				89	1.05	48.425
4S V15.tif				189	1.023	48.091
4S V16.tif				170	0.998	47.867
5S H1.tif				415	0.904	24.327

SPECIMEN	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
5S H2.tif				403	0.932	25.201
5S H3.tif				638	0.653	17.227
5S V11.tif				361	1.578	47.612
5S V12.tif				148	1.633	50.6
5S V13.tif				170	1.577	47.731
3E H1.tif				289	0.448	33.201
3E H2.tif				397	0.326	23.912
3E H3.tif				422	0.31	22.244

SPECIMEN	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	**After test**	**Analysed**			
3E V1.tif				140	0.524	45.45
3E V2.tif				174	0.537	44.197
3E V3.tif				142	0.541	46.061
4E H1.tif				304	1.543	66.791
4E H2.tif				223	1.091	48.403
4E H3.tif				275	0.869	37.703
5E H4.tif				357	1.36	37.938
5E H5.tif				661	1.224	34.512

SPECIMEN	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
5E H6.tif				519	2.744	75.604
5E V1.tif				209	1.594	47.946
5E V2.tif				174	1.579	48.806
3T H9.tif				159	0.332	25.436
3T V16.tif				56	0.514	41.567
4T H1				19	1.567	68.295
4T V8				11	1.603	73.206
5T H.tif				160	0.34	26.415

ImageJ metrics of Count, Total Area, and %Area representing the segmented feature in the QR-code region of interest (ROI) after tensile testing. Results are aggregated by application technology (S = sublimation; T = heat transfer; E = embroidery), nominal QR size (2 = 20 mm, 3 = 30 mm, 4 = 40 mm, 5 = 50 mm), and test direction (H, V). Note: Not all tensile specimens are listed. In some images, it was not possible to binarize/segment the QR region reliably in ImageJ, and those specimens were removed from quantitative analysis**.**

4.4.1. Analytical Approach and Data Inclusion

Photography of QR-code specimens was carried out before and after tensile testing. Post-test images were evaluated in ImageJ with a consistent thresholding and particle/region counting procedure (e.g., Analyze Particles) within an ROI that included the QR-code space. Three quantities were reported for each sample: Count (number of detected regions); Total Area (sum of the areas of all detected regions; where applicable, this was reported in calibrated units rather than pixel counts); %Area (fractional area covered by detected regions with respect to the ROI). Samples were characterized in terms of application technology: S (sublimation), T (heat transfer), and E (embroidery), and nominal QR size: 2 (20 mm), 3 (30 mm), 4 (40 mm), or 5 (50 mm). A subset of samples was therefore removed (binarization being inconsistent), as ImageJ processing did not enable stable binary separation and segmentation for the QR region, which would have allowed extraction of reliable metrics. For this reason, only samples with complete and internally consistent ImageJ outputs were included in the analysis (n = 41).

4.4.2. Technology Level Comparison (S, E, T)

When technology was considered, mean %Area was:

- Sublimation: mean 34.072% (SD 12.879; range 16.647–50.600%)
- Embroidery: mean 43.769% (SD 14.523; range 22.244–75.604%)
- Heat transfer: mean 46.984% (SD 22.685; range 25.436–73.206%)

On closer inspection, embroidery and heat transfer show higher mean %Area than sublimation, with greater spread.

4.4.3. Directional Dependence (H vs V)

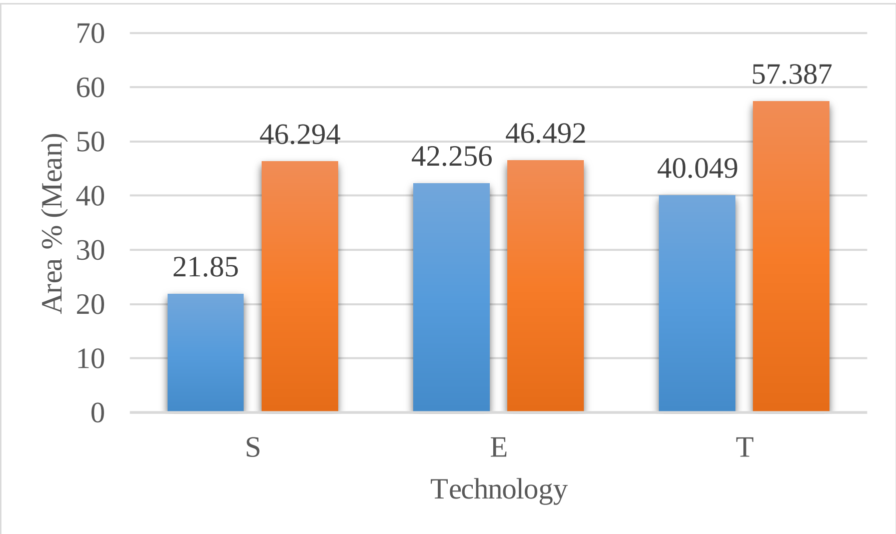


Fig. 17. Mean Area% by Application Technology and Test Direction (H vs V)

A directional effect is evident across technologies:

- H direction (n = 23): mean %Area 32.209% (SD 16.857)
- V direction (n = 18): mean %Area 47.582% (SD 6.933)

Thus, the %Area is much higher on average in the V-direction samples. This trend is still observed in the technology-stratified data and is strongest for sublimation.

Collectively, the results suggest that test direction is a significant factor, consistent with directional deformation behaviour in textile materials and different responses to tensile loading exhibited by the applied QR layer.

4.4.4. Size-Related Patterns and Confounding

Likewise, mean Area% also varied by nominal size (20 mm 32.279%, 30 mm 35.144%, 40 mm 45.268%, and 50 mm 40.327%). At the same time, size effects are not independent because technologies and directions are not evenly distributed across sizes and some strata have small sample sizes. In sublimation, mean %Area is relatively uniform across sizes within the same direction, but the H–V separation remains large (direction effect > size), indicating a general tendency for direction effects to dominate over size effects in this subset.

4.4.5. Count, Total Area, and Area%

The %Area is positively and strongly correlated with Total Area (r = 0.739) and negatively but moderately correlated with Count (r = −0.593) across all specimens. This suggests that larger Area% values are generally caused by larger continuous areas of the segmented feature rather than many small regions. Thus, %Area provides coverage, and Count provides additional information on connectivity or shape.The peak Area% values were recorded for 5E H6 (75.604%), 4T V8 (73.206%), 4T H1 (68.295%), and 4E H1 (66.791%). The lowest value was 4S H1 (16.647%). These extremes demonstrate that the combination of technology, size, and test direction can lead to strongly diverging post-test images.

4.5. Results Analysis of Image-Based Geometric Change After ISO 6330 Washing

Across all analysed specimens (n = 24), Area% ranged from 7.591% to 69.529% (mean 27.637%, median 18.891%, SD 18.424). Total Area ranged from 0.186 to 1.621 (mean 0.573, median 0.435, SD 0.388), while Count ranged from 16 to 625 (mean 222.625, median 200, SD 170.790). Average Size ranged from 0.000416 to 0.101 (mean 0.010876, median 0.002500, SD 0.022433), indicating a strongly skewed distribution driven by a small number of large detected regions in some specimens. The Mean value is constant (255) for all specimens, suggesting a fixed measurement outcome from the binarized images; therefore, it does not contribute to between-sample variability in this dataset.

Table 14. Image analysis of home laundering tested specimen

SAMPLES	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
W-3E-17				32	0.698	50.933

SAMPLES	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
W-3E-18				39	0.667	48.513
W-3E-19				46	0.712	51.269
W-4E-16				29	1.558	65.197
W-4E-17				16	1.621	69.529
W-4E-19				427	0.396	16.97
W-5E-18				191	1.203	33.261
W-3S-21				259	0.273	19.687
W-3S-22				185	0.357	25.833
W-3S-23				195	0.533	39.986

SAMPLES	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
W-4S-11				524	0.445	18.094
W-4S-12				625	0.26	10.678
W-4S-20				73	0.829	34.3
W-5S-18				206	0.618	16.481
W-5S-19				545	0.398	10.677
W-3T-14				275	0.186	13.938
W-3T-15				126	0.419	31.87
W-3T-18				56	0.485	36.914
W-4T-14				292	0.237	9.866

SAMPLES	IMAGE			COUNT	TOTAL AREA	%AREA
	Before test	After test	Analysed			
W-4T-15				322	0.214	9.116
W-4T-18				229	0.369	15.643
W-5T-14				205	0.425	11.558
W-5T-15				156	0.572	15.373
W-5T-16				290	0.278	7.591

4.5.1. Technology-Level Comparison (S, E, T)

Differences were easily distinguished by product technology:

1. Embroidery (E; n = 7): mean Area% = 47.953 (SD 18.069, range 16.970–69.529%); mean Average Size = 0.030847
2. Sublimation (S; n = 8): mean Area% = 21.967% (SD 10.670; range 10.677–39.986%); mean Average Size = 0.002750
3. T Heat (n = 9): mean Area% = 16.874% (SD 10.384; range 7.591–36.914%); mean Average Size = 0.002568

Embroidery has the highest mean Area% and a greater inter-sample spread, whereas both sublimation and heat transfer method have lower mean Area% values in the present W-series panel. Interpretation of technology comparisons should take differences in subgroup size into account.

4.5.2. Confounding and Patterns of Effects Related to Size (30–50 mm)

Average %Area difference per nominal size was:

1. 30 mm (n = 9): mean 35.438% (SD 13.692; range 13.938–51.269%)
2. 40 mm (n = 9): average 27.71% (SD 23.731; range 9.116–69.529%)

3. 50 mm (n = 6): average 15.824% (SD 9.134; range 7.591–33.261%)

Size effects are not independent, however, with variation in technology composition across sizes and restricted n for some strata. The large SD at 40 mm is due to the fact that both very low T values and very high E values are present in this group.

4.5.3. Count, Total Area, and %Area

More broadly, across all specimens, %Area was highly positively correlated with Total Area (r = 0.819) and similarly associated with Average Size (r = 0.787), but inversely related to Count (r = −0.737). This means that higher %Area results are due mainly to high Total Area and high Average Size of the connected regions, not many small fragmented regions (higher Count). Thus, %Area reflects coverage/extent, Total Area captures the magnitude of segmented regions, and Average Size serves to explain whether the result is because of one or a few larger regions rather than many small ones.The maximum %Area was observed in W-4E-17 (69.529%) and W-4E-16 (65.197%), and the minimum value was W-5T-16N (7.591%). High values cluster in embroidery (E) specimens, with the low in heat transfer (T) and some sublimation (S), indicating significant divergence of ImageJ results based on technology–size pairings within the W-series set.

4.6. Chapter Summary

This chapter studied the legibility and scanning reliability of QR codes on a stretchable fabric (polyester–spandex interlock) via a 23 factorial design with the factors being QR code size, application method, and the direction of the fabric. Multicycle tensile tests confirmed fabric anisotropy, with the vertical (wale) direction supporting greater loads and retaining greater permanent set than the horizontal (course) direction. Additionally, peak force reduced from Cycle 1 to Cycle 5, indicating mechanical conditioning during repetitive loading. Post-cycling (thickness) measurements showed a similar trend, with higher thickening in the V direction achieved by ALL methods.

QR functionality had also been largely determined by application technology and the smallest code size achievable in practice. Sublimation was consistently readable at sizes ≥20 mm and heat transfer continued to be fully readable across the range tested (30–50 mm). Embroidery showed the worst performance; that is, readability could not be retained after tensile loading even with partial baseline readability at some larger font sizes. Independent of the labeling method, fabric shrinkage could be considered moderate after ISO 6330 washing, while the effects on QR geometry were significantly more variable. Readability was preserved for sublimation and heat transfer while embroidery demonstrated substantial one-way distortion, with greater loss of scan reliability. These observations were corroborated by ImageJ analysis, revealing significant method- and direction-specific geometry alterations of the QR region following exposure. In summary, all findings define the practical threshold of durable QR labeling on heat-transfer (≥30 mm) and sublimation (≥20 mm) provide the best compromise between functional durability and scan stability while embroidery is not recommended if the fabric will be frequently stretched or washed. As a Digital Product Passport is accessed digitally, the QR code needs to function as a reliable access key for linking the physical garment with its DPP record online. This implementation is illustrated in the subsequent chapter by generating customised QR codes and also hosting them on Google that satisfy the validated durability requirements, wherein upon scanning a link provided by Google opens up and can be personalized henceforth to show stored information content using DPP website.

5. Practical Deployment of DPP Implementation Using Google Sites

The implementation of the Digital Product Passport (DPP) system was done in practice with Google Sites as a main web-based tool and dynamic QR codes to facilitate the interface personalized link to connect each physical product with its digital record. The system worked in a process, which involved input of information about merchandise into a Google Sheet saved on cloud space, displaying the items curated on Google Sites through an embedded interface and access by scanning dynamic QR code. Each T-shirt, along with the sample TS-0001, will have a unique Serial Number which is also its digital identity in the database.

Fig. 18. Consumer view of product information on the DPP website

Once the QR code is scanned on the garment, consumers will be taken to DPP's website where they can enter in serial number and receive all product information instantly, including fiber composition, origin of material and production route, care instructions plus sustainability information.

5.1. DPP System with Google Sites with Main Features

The DPP system created with Google Sites offers a simple and affordable way to share clear product information with consumers and supply-chain partners.

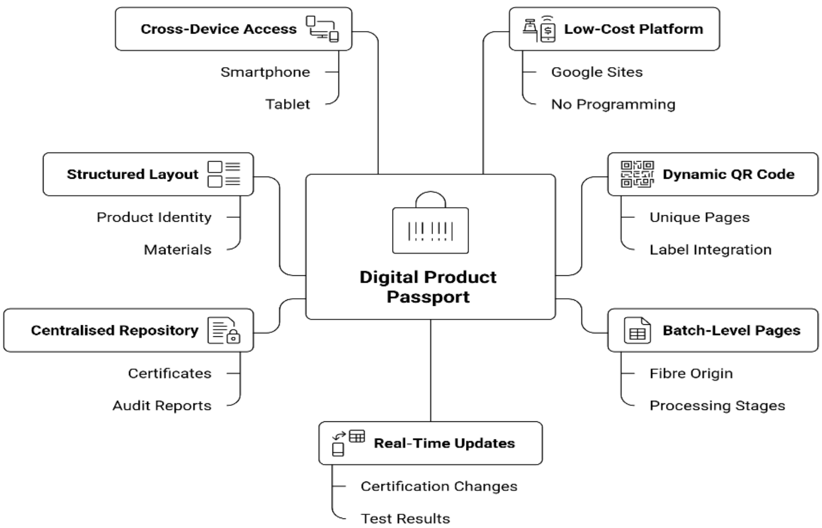


Fig. 19. DPP website features

Each item is connected to its own online page through a dynamic QR code, making it easy to trace materials, processes and certifications. Because the pages can be updated instantly and viewed on any device, the system provides a practical and transparent solution for everyday use.

Table 15. Key Features of the Google Sites–Based Digital Product Passport System

Key feature	Description
Low-cost, accessible platform	Built on Google Sites with no programming knowledge and minimal financial investment needed, making it suitable for small and medium-sized enterprises.
Dynamic QR code integration	A dynamic QR code printed on the label or packaging is associated with a unique Google Sites page for each garment or batch.
Batch- and product-level pages	Dedicated pages are created for specific SKUs or batches, containing structured data about fibre origin and processing stages (when and where).
Real-time data updating	Content can be modified at any time, enabling quick updates when certifications change, new test results are received, or process data are adjusted.
Centralised document repository	Certificates (such as GRS, OEKO-TEX), audit reports, lab tests and logistics documentation can be embedded or linked directly on the DPP page.
Structured information layout	Pages are divided into sections (product identity, materials, process timeline, logistics and certificates) to ensure a clear and readable layout.
Cross-device accessibility	The DPP is accessible via smartphone, tablet or computer, allowing consumers and stakeholders to access it at the point of purchase or use.

5.2. Design and Structure of the Digital Product Passport Website

5.2.1. Homepage Overview

The home page provides an overview of the Digital Product Passport and displays the principal thematic sections in a comprehensible, well-organised format. It serves as a hub to visit from where one will be able to navigate to the details on traceability, sustainability, compliance, and product lifecycle stages. It's beautifully simple to use, slick and easy on the eye with all the information you need right there at your fingertips, clearly laid out and logically presented.

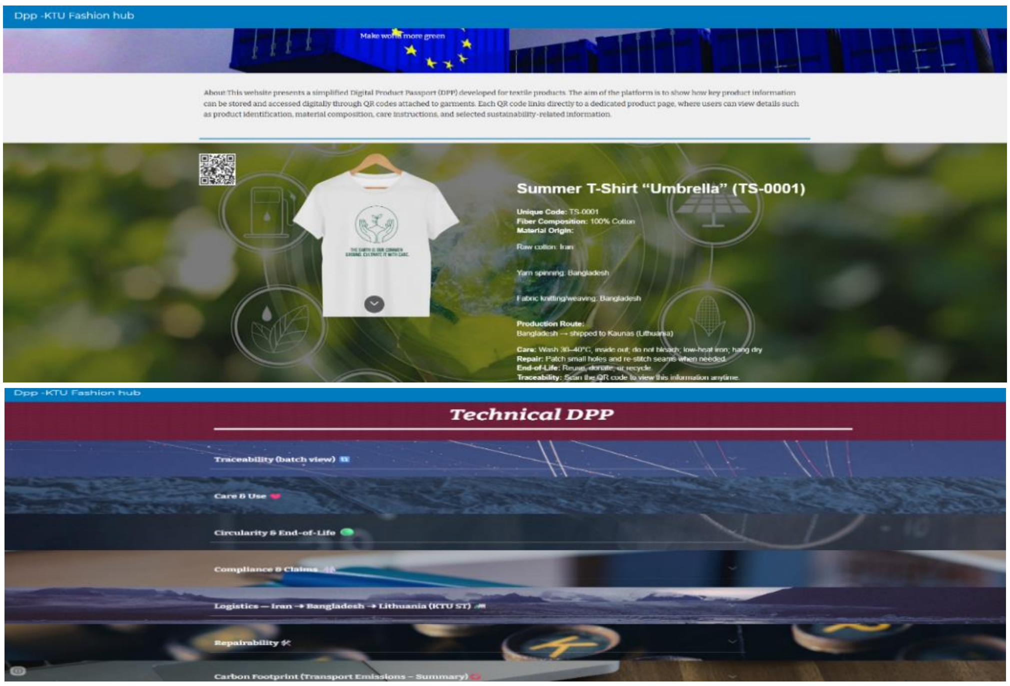


Fig. 20. Home page of the website

5.2.2. Traceability Section

This section covers the garment's full cycle from raw materials to the end product. It consists of the birthplace of cotton, its processing cycle in Bangladesh, and how it is finally moved to Lithuania. All steps are described in order of their occurrence along with the location, description of the step, and production dates. The purpose of this section is to provide full visibility into the supply chain and show responsible sourcing principles.

5.2.3. Care & Use Section

A Care & Use section offers tips on how consumers can care for the garment to extend its life. It comprises wash care, dry and ironing instructions applicable to textile standard. This department promotes sustainable consumption through responsible use and care of products, delaying their disposability and increasing durability.

5.2.4. Circularity & End-of-Life Section

This section highlights the product's fit with principles of circular economy. It features tips for ways to reuse, repair, donate or recycle the clothing after it is worn out. The descriptions direct consumers toward more environmentally friendly disposal routes and in line with EU requirements for circular textile systems.

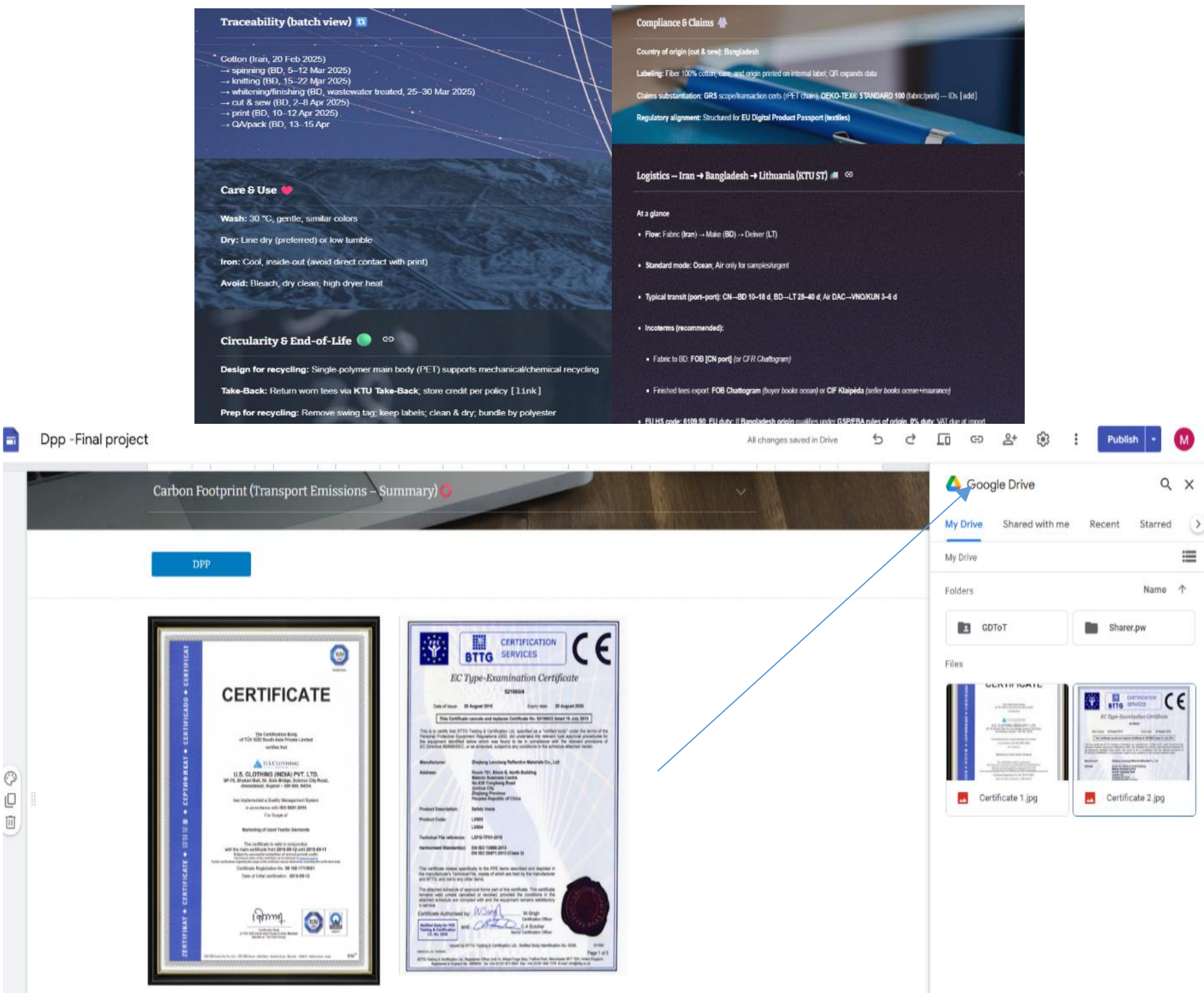


Fig. 21. Product information on DPP websites

5.2.5. Compliance & Certificates Section

On this part of our website, we are integrating related sustainability certifications, audit reports and material test results within the page. Examples are GRS, OEKO-TEX or BSCI/SMETA certificate. As certified documentation is shown in this section it offers more credibility for sustainability declarations and direct evidence of meeting textile and environmental standards.

5.2.6. Logistics & Distribution Section

The logistics component illustrates the methods of transportation and movement of goods in process and finished products. It details the travel of fabric and clothing from where they are made to a distribution center, in this case Lithuania how long it usually takes, which routes goods take on standard shipping roads, carbon footprints. This chapter illustrates how logistics affect the total product environment effect.

5.2.7. Repairability Section

This is a section regarding product repair rather than replacement. This includes recommendations for typical wear or repair items . It is aligned with the EU textile ecodesign approach, with a focus on durability, reparability and long lifetime.

Fig. 22. Mobile view of website and dynamic QR code

5.2.8. QR Code and Digital Access

A dynamic QR code is connected to the website and can be printed onto the item’s label or packaging. When consumers scan, it links them directly to the product’s DPP page so that they can read up on the product right there and then. The site is mobile-friendly-optimized for use on any device--and promotes access to information at the time of purchase or application.

5.3. Website Security

The DPP website is powered by Google Sites, and is covered automatically by the security protection system of Google. All the pages load on HTTPS so the connection is secure and safe. Only that admin decides to share, while more sensitive or internal information remains classified.
Each tag and document, such as certificates, are uploaded as protected files that cannot be changed or edited. Google also maintains updates, the result being that it's always the most current version of your information displayed on our site. The QR code redirect link is pointing to a public DPP page, therefore, the product information is shown, but private hidden data isn’t disclosed. The site is clean, secure, and safe for consumer utilization.

5.4. Why This DPP Website Works Well for SMEs

This Digital Product Passport is well suited for small and medium-sized businesses because it is simple to set up, easy to manage, and requires almost no financial investment. Since the website is created through Google Sites, companies do not need advanced technical skills, professional developers or paid digital tools. Teams can update the information themselves, which is helpful for SMEs that often work with limited time and resources.The system is also flexible. New certificates, production data or batch information can be added whenever needed, allowing the passport to stay current. The dynamic QR code gives customers quick access to the product’s information, helping companies remain transparent without high costs. As the website works smoothly on phones, tablets and computers, it becomes easy to use in daily business operations. Overall, this approach offers SMEs a practical way to share trustworthy product information and respond to increasing sustainability requirements, while keeping both effort and expenses low.

5.5. Chapter Summary

This chapter illustrates how to implement a Digital Product Passport (DPP) through the use of Google Sites as web platform, Google Sheets as cloud data source and dynamically generated QR codes linking physical garments to their respective digital product pages. On scanning the QR code, users can access information about the product at a glance like fibre description such fibre composition, material origin and production route as well as care instructions, sustainability aspects and certificates.

The DPP site has divided its main menu into visual chapters (homepage, traceability, care & use, circularity/end-of-life, compliance & certificates, logistics…) to facilitate navigation and the transparency of a responsible approach. Google Sites offers rudimentary security through admin-controlled sharing and is therefore usable in the consumer space. On the whole, this is a good strategy for SMEs as it’s cost-effective and can be updated in real time without technical experience.

Conclusions

1. The analysis of the EU ESPR and textile DPP context shows that, for fashion companies, a DPP can only work effectively when product and sustainability information is shared in a consistent and reliable way across the full product lifecycle. Therefore, durable labeling is not optional; it is a practical requirement for making DPP access and verification possible in real use.
2. The technology review indicates that, compared with RFID and NFC, QR codes are the most practical and scalable option for garment DPPs. They are inexpensive, easy to deploy, and can be accessed by consumers with any smartphone, whereas RFID and NFC offer additional capabilities but typically require higher investment, supporting infrastructure, and more complex standardisation.
3. The testing results show that QR codes can be used reliably on textiles, but their success strongly depends on how they are applied and how large they are.The experimental research have proved, that during repeated stretching, the fabric did not fully return to its original shape, especially in the vertical direction, and this permanent deformation affected the shape of the QR codes. This explains why some codes became difficult or impossible to scan after testing. The results confirm that durable QR-based Digital Product Passports on garments are achievable when heat transfer or sublimation printing is used at appropriate sizes, while embroidery is not suitable for applications that require long-term, real-world functionality.Sublimation-printed QR codes worked well as long as the size was at least 20 mm, remaining fully readable even after stretching and five wash–dry cycles, while smaller 10 mm codes failed because the QR modules were simply too fine to survive deformation.Heat transfer printing showed the most stable behaviour overall, with all tested sizes between 30 and 50 mm remaining fully readable after both mechanical loading and washing.Embroidery, on the other hand, proved unreliable: smaller embroidered codes were unreadable from the beginning, and even larger ones that initially scanned partially lost all functionality after use-related stress. Image analysis clearly supports this, showing much higher distortion in embroidered QR codes compared with sublimation and heat transfer.
4. The study demonstrates that a simplified DPP can be implemented successfully using Google Sites with a cloud-based data source and dynamic QR access. This approach allows structured product information to be presented clearly, updated in real time, and accessed easily by consumers, while maintaining basic security through HTTPS and administrator-controlled sharing. Overall, it provides a feasible, low-cost pathway for SMEs to adopt DPP functionality in daily operations.

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Appendices

APPENDIX 1.

Certificate of Participation in the 12th International Young Researchers' Conference"Industrial Engineering 2025" (Kaunas, 15 May 2025). This appendix presents a copy of the certificate confirming the author's participation in the 12th International Young Researchers' Conference "Industrial Engineering 2025", held in Kaunas on 15 May 2025. Participation in this international academic conference contributed to the author's scholarly development and provided exposure to current research trends and discussions relevant to the field of industrial engineering and logistics.

Figure A1.1. Certificate of Participation in the 12th International Young Researchers' Conference "Industrial Engineering 2025", Kaunas, 15 May 2025.

APPENDIX 2.

Certificate of Participation in the IX International Scientific-Practical Conference of Textile and Fashion Technologies (Kyiv, 16 October 2025).

This appendix presents a copy of the certificate confirming the author’s participation in the IX International Scientific-Practical Conference of Textile and Fashion Technologies, held in Kyiv on 16 October 2025. Participation in this international conference contributed to the author’s academic development and supported the research perspective in the fields of textile technologies, fashion innovation, and sustainability, which are directly relevant to the topic of the thesis.

Figure A2.1. Certificate of Participation in the IX International Scientific-Practical Conference of Textile and Fashion Technologies, Kyiv, 16 October 2025