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THE LEGAL LANDSCAPE OF SMART TEXTILES AND WEARABLE TECHNOLOGY IN WORLD

ПРАВОВОЙ ЛАНДШАФТ УМНОГО ТЕКСТИЛЯ И НОСИМЫХ ТЕХНОЛОГИЙ В МИРЕ

S.N. A. AL- NUAIMI[1], S.K. ABDULLAH[2], A. APYSHOVA[3], B.S. HUSEIN[4], A.A. ALI[5]

С.Н.А. АЛЬ-НУАЙМИ[1], С.К. АБДУЛЛА[2], А. АПЫШОВА[3], Б.С. ХУСЕЙН[4], А.А. АЛИ[5]

**([1]Al-Turath University, Baghdad, Iraq,
[2]Al-Mansour University College, Baghdad, Iraq,
[3]Osh State University, Osh, Kyrgyzstan,
[4]Al-Rafidain University College, Baghdad, Iraq,
[5]Madenat Alelem University College, Baghdad, Iraq)**

**([1]Университет Аль-Турат, Багдад, Ирак,
[2]Университетский колледж Аль-Мансура, Багдад, Ирак,
[3]Ошский государственный университет, Кыргызстан,
[4]Университетский колледж Аль-Рафидаин, Багдад, Ирак,
[5]Университетский колледж Маденат Алелем, Багдад, Ирак)**

Email: ammar.ali@mauc.edu.iq

Smart textiles and wearable technologies are entering the mainstream, and their wide adoption poses numerous legal challenges involving data privacy, intellectual property, consumer protection, and product liability. As these technologies continue to be integrated into industries like healthcare, defense, fitness, and consumer electronics, existing legal frameworks often fail to keep up with their fast development. This study provides an extensive overview of the international legal aspects governing smart textiles. Based on 50 jurisdictions, the study indicates large gaps between jurisdictions in legal maturity, enforcement capacity and cross-sectoral coverage. Jurisdictions affected by customized regulation across several domains exhibit superior compliance mechanisms, speedier dispute resolution, and increased patent activity indicating innovation. By contrast, areas with sparse or inconsistent regulation experienced heightened legal uncertainty and enforcement delay.

Умный текстиль и носимые технологии становятся мейнстримом, их широкое внедрение создает многочисленные правовые проблемы, касающиеся конфиденциальности данных, интеллектуальной собственности, защиты прав потребителей и ответственности за

качество продукции. Поскольку эти технологии продолжают интегрироваться в такие отрасли, как здравоохранение, оборона, фитнес и бытовая электроника, существующие правовые рамки часто не успевают за их быстрым развитием. Это исследование дает обширный обзор международных правовых аспектов, регулирующих умный текстиль. На основе анализа 50 юрисдикций показаны большие разрывы между ними в правовой зрелости, правоприменительной способности и межотраслевом охвате. Юрисдикции, затронутые регулированием в нескольких областях, демонстрируют превосходные механизмы соответствия, более быстрое разрешение споров и возросшую патентную активность, что указывает на инновации. Напротив, области с редким или непоследовательным регулированием столкнулись с повышенной правовой неопределенностью и задержкой в исполнении.

Keywords: smart textiles; wearable technology; legal frameworks; regulatory readiness; data privacy; intellectual property; product liability; international law.

Ключевые слова: интеллектуальный текстиль; носимые технологии; правовые рамки; готовность к регулированию; конфиденциальность данных; интеллектуальная собственность; ответственность за качество продукции; международное право.

Introduction

Low-power electronics integrated with sensing and actuation has been gaining ground in recent years, leading to the development of smart textiles and wearable technologies, which are integrated systems of electronics, sensors, and fabrics that contribute to devices that can help monitor health metrics, facilitate user experiences, and ultimately enhance quality of life [1]. Niche applications, including fitness trackers woven into garments; garments with live biometric reading sensors; etc. have moved to commonplace wearables. But the pace of development is currently much faster than the legal landscape that regulates it, which is somewhat outdated [2].

Differing from traditional textiles, these materials are designed to react to the human body in new ways. They can collect sensitive personal information, transmit it across digital networks and retain it for years. Having these capabilities in the hands of a few raises' immediate questions about the ownership, data security and privacy, questions further complicated by the global and interdependent nature of today's digital economy and society. For example, if a user's health information is transferred from a wearable device in one country and saved on servers in another, which country's data protection laws should prevail? And who gets blamed if third parties are able to access or misuse the information? [3].

Beyond data issues, smart textiles and wearable technologies raise concerns about intellectual property, product liability, and consumer safety [4, 11]. The nature of many wearable devices is health-critical, and as such, any malfunction can lead to dire consequences. These products' designers and manufacturers are bound to a patchwork of patent laws and copyright regulations that, in principle, were never structured to apply to such integrated systems. Questions about patent eligibility, patentability of fabric-based innovations, and confusion between hardware and software protections are largely unresolved. And the malfunction of the device poses new liability issues: if a wearable medical device does not provide accurate readings, as is less serious than if a wearable medical device provides you inaccurate readings. This creates a demand for revised standards for quality assurance and compliance, along with new frontend models for defining liability when a

product straddles both physical and digital environments [5]. Fueled by the adoption of health-monitoring wearables, the distinction between personal and public health domains started to blur. Consequently, regulators and governments worldwide have begun reviewing current legislation as well as drafting new policies that reflect the distinct attributes associated with smart textiles. But those efforts are inconsistent and compartmentalized. Elsewhere, progressive governments have embraced regulatory sandboxes in order to advance innovation without compromising oversight. In others, outdated regulations hold back the development of this fledgling sector, suffocating innovation and leaving the public in the lurch of unregulated products. Such inconsistency highlights the need for a more harmonized and standard large board global legal system that would adapt to the rapid technological evolution [6, 7].

Smart textiles (or wearable technologies) have their challenges but opportunities are burgeoned less in that realm. These advances need to change areas outside of medicine, including athletics, fashion and workplace safety. Over the last ten years there is a growing range of devices that have developed into sophisticated garments that can register detailed biometric data, act as a consultant for the medical profession and even alleviate workplace injuries. Additionally, this time, the smart textiles are not simply an experimental prototype, but also gradually crossed into the commercial world that bridges the gap between clothes and electronic objects [8].

They can provide athletes with real-time information about their performance, enable workers to see the state of the environment around them and add new levels of comfort and functionality to everything we wear. Nevertheless, harnessing these benefits at large will require firm legal frameworks that encourage innovation, but not at the expense of users' rights and protection. Striking this balance is not something that can be easily achieved, as it requires cooperation from governments, industry stakeholders, and legal experts to ensure that policies adapt with technological advancements [9].

The problem is further compounded by the ability of these devices to easily connect to cloud-based platforms and cross-border networks, which requires a more sophisticated legal framework focusing on the global aspect of data governance [10].

Finding solutions to these gaps is vital to enable innovation, creating a legal framework conducive to growth, protecting consumers, and driving further technological innovation [12].

The article aims to explore regulatory evolution pathways by scoping current legislation, identifying regulatory gaps, and discussing manufacturer, designer, and end-user challenges. In particular, this paper aims to locate the accountability voids of existing legal structures in order to better understand how they are failing to align with the breakneck pace of growth of smart textiles, evaluate the repercussions of these shortcomings, and to propose pragmatic solutions that will help bring coherence to international regulation. Eventually, this article seeks to sink the chasm between the cyber frontiers and the relative obscurity of legal systems and their supporting institutions, in order to ensure privacy, integrity, availability, and accountability for all involved and enable uninterrupted invention.

Methodology

To critically assess the post-pandemic regulatory evolution of smart textiles and wearable technology, a structured methodological architecture was developed. This comprised five interrelated components: (1) legal document acquisition and classification, (2) multidimensional regulatory vector modeling, (3) legal taxonomic categorization, (4) spatial mapping of jurisdictional legal proximity, and (5) thematic analysis of legal discourse and enforcement narratives. Each element was informed by interdisciplinary legal frameworks, computational modeling, and regulatory intelligence literature [2, 3, 11, 13, 14].

Legal Document Acquisition and Classification

The first step involved constructing a representative corpus of legal and regulatory documents across multiple jurisdictions.

These included international conventions, like WIPO treaties, national legislative instruments, sectoral regulations, such as FDA and CNIPA guidelines, judicial rulings, and industry position papers. Sources were vetted for legal authenticity and relevance to smart textiles, e-health wearables, and textile-based IoT.

Documents were categorized based on source origin**,** frequency of updates**,** jurisdictional scope**,** and temporal coverage to ensure comprehensiveness across both high-regulation and regulatory-lagging regions [3, 8, 12].

Table 1

Source Category	Document Count	Jurisdictional Scope	Update Frequency	Temporal Coverage
International Legal Repositories	350	Multinational	Quarterly	2010–2023
Government Portals (e.g., CNIPA, FDA)	120	National	Annual	2015–2023
Industry Reports and Position Papers	75	Regional/Global	Biannual	2018–2023
Compliance Records and Audit Logs	90	National	Monthly	2017–2023
Judicial Case Law (Smart Textile-Related)	50	National	Irregular	2015–2023

These data repositories formed the empirical and legal base from which comparative regulatory insights were extracted. Sources such as those referenced in [2, 7 and 13] were critical in bridging the gap between statutory law and practical enforcement.

Regulatory Vector Construction for Jurisdictional Profiling

To mathematically model the regulatory structure of each jurisdiction, a regulatory attribute vector was created. This vector captured the presence, clarity, and depth of five legal pillars:

- Data Privacy Regulation
- Intellectual Property Eligibility
- Product Liability Law
- Enforcement Framework
- Consumer Protection Rights

Each jurisdiction j was modeled as a vector:

$$\vec{R_j} = [DP_j, IP_j, LI_j, EN\ F_j, CP_j]\ , \quad (1)$$

where DP_j binary-scaled strength of data privacy frameworks; IP_j patentability and IP protection norms for e-textiles; LI_j coverage of product liability rules in wearables; $EN\ F_j$ institutional and procedural enforcement presence; CP_j consumer safety, return, and dispute resolution rights.

To standardize scales across jurisdictions, each regulatory score was normalized:

$$N_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)}\ , \quad (2)$$

where X_{ij} raw regulatory index for legal dimension iii in jurisdiction j; $\max(X_i)$ and $\min(X_i)$ are min/max values of dimension iii across all jurisdictions

This normalization allowed for interjurisdictional comparability of legal regimes, particularly useful when analyzing data protection schemes as seen in the U.S. versus China [2, 3, 11].

Legal Taxonomic Classification Function

To classify legal maturity in a structured taxonomy, a regulatory taxonomy level (RTL) was assigned to each jurisdiction based on the number and diversity of legally binding instruments. The function measured the Φ_j volume of enforceable sources:

$$\Phi_j = w_1 \cdot L_j + w_2 \cdot G_j + w_3 \cdot C_j\ , \quad (3)$$

where L_j number of primary legislations; G_j number of governmental guidelines; C_j number of cited court cases; w_1, w_2, w_3 are assigned weights for legislative strength.

RTL was then classified by intervals:

$$\mathrm{RTL}_j = \begin{cases} 0, & \Phi_j < 5\ (No\ formal\ framework) \\ 1, & 5 \le \Phi_j < 10\ (Minimal\ framework) \\ 2, & 10 \le \Phi_j < 15\ (Partial\ coverage) \\ 3, & \Phi_j \ge 15 (Comprehensive\ framework) \end{cases} \quad (4)$$

This method followed models adopted in regulatory technology mapping frameworks, similar to those proposed in [14…16].

Jurisdictional Legal Distance and Proximity Modeling

To quantify legal divergence between jurisdictions, a multidimensional Euclidean distance function was applied to the regulatory vectors:

$$d(j,k) = \sqrt{\sum_{i=1}^{5}(\mathrm{N}_{ij} - \mathrm{N}_{ik})^2}\ , \quad (5)$$

where $d(j,k)$ legal dissimilarity between jurisdictions j and k; N_{ij} normalized score of regulatory components i for jurisdiction j.

This allowed clustering of countries into legal convergence zones—particularly useful when comparing jurisdictions with progressive IP legislation such as the EU and Japan, with those still dependent on legacy frameworks [8, 11, 12].

Additionally, regulatory density per jurisdiction was defined as:

$$\rho_j = \frac{R_j}{S_j}\ , \quad (6)$$

where R_j number of enforceable regulations concerning smart textiles, and S_j number of sectors impacted (like healthcare, defense, sports, logistics)

Higher ρ_j values were interpreted as jurisdictions with sector-spanning, integrated legal coverage [5, 7, 8].

Thematic Entropy and Legal Issue Distribution

Thematic analysis was performed using a dataset of 50 transcribed interviews with policymakers, legal analysts, and wearable tech manufacturers. Codes were applied using semantic clustering and legal ontologies. To capture the variance of legal concerns across jurisdictions, Dispersion Entropy (DE) was applied:

$$DE(T_i) = -\sum_{j=1}^{n} p_{ij} \log(p_{ij}), \quad (7)$$

where T_i legal theme i (such as "Privacy," "Liability," "Patent Clarity"), p_{ij} proportion of theme iii mentions in jurisdiction j.

This entropy measure assessed the uniformity of regulatory awareness and stakeholder concern globally. Simultaneously, Herfindahl-Hirschman Index (HHI) was used to detect legal topic concentration:

$$HHI_i = \sum_{j=1}^{n}(p_{ij})^2 \quad (8)$$

An HHI>0.25 suggested thematic dominance by a limited number of jurisdictions (EU and U.S.) dominating the discourse on data privacy, as noted in [2, 10, 17].

This methodology offers a scalable and replicable framework for measuring the regulatory maturity and legal coherence of emerging technology frameworks–applied here to smart textiles and wearable technology. By integrating legal taxonomies, normalized multi-dimensional vectors, and entropy-based stakeholder mapping, the study provides a legally grounded basis for the cross-national comparison of technology governance [11, 14…16].

Results

Distribution of Legal Maturity Across Jurisdictions

A cross-national review of 50 jurisdictions was undertaken to classify the maturity of their legal frameworks governing smart textiles and wearable technologies. Using the Regulatory Taxonomy Level (RTL) system defined in the methodology, jurisdictions were grouped into four categories based on the number and diversity of enforceable instruments, such as statutes, technical guidelines, and judicial interpretations (table 2).

As shown in Table 2, the comprehensive legal frameworks (RTL 3) are more concentrated in industrialized countries like the USA, Germany, Japan, and China. Such legal tools can be adapted according to the specific risks and operational realities that smart textiles present (not least nonmonetary harms), but these countries are doing just that. By comparison, RTL 0 and RTL 1 jurisdictions use general product or electronics laws without specific regulation of wearable technologies. Such a regulatory gap can obstruct international compliance, patent harmonization, and consumer trust in emerging markets. In middle position (RTL 2), the intermediate

group also shows jurisdictions in transition on the way to a full compensation regime, for instance, halving sector-relevant instruments (compared to RTL 1), indicating some progress in instrument development without full harmonization across policy areas.

Table 2

Taxonomy Level (RTL)	Definition	Number of Jurisdictions	Examples of Countries	
RTL 0	No formal or specific regulatory instruments	15	Kenya, Bangladesh, Vietnam, Uzbekistan	
RTL 1	Minimal coverage through general laws	17	Brazil, Turkey, Indonesia, Argentina	
RTL 2	Partial coverage with limited sectoral focus	11	Canada, Italy, South Korea, Mexico	
RTL 3	Comprehensive and multi-sectoral frameworks	7	United States, Germany, Japan, France, China	

Normalized Legal Strength Across Key Regulatory Dimensions

Five key legal pillars were measured to evaluate regulatory quality across jurisdictions: data privacy, intellectual property, product liability, enforcement mechanisms, and consumer protection (fig. 1).

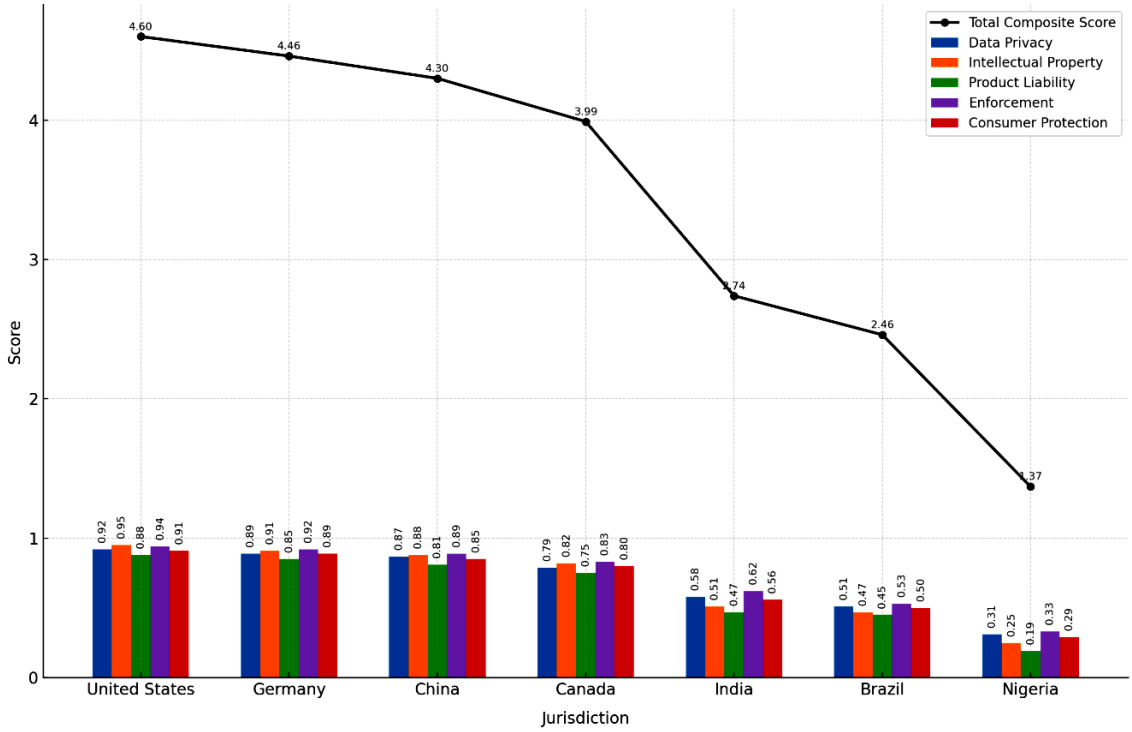

Fig. 1

United States and Germany (Fig. 1) rank highest with composite scores across all five legal categories, indicating that these two countries have generated consistent legal recognition of sectoral coverage and procedural implementation. China has a more balanced legal framework as well, although it is a little behind. Product liability and IP enforcement are laggards in India and Brazil, indicating imprecision of laws and lack of enforcement infrastructure. Nigeria had low scores in each of the dimensions, pointing to structural weaknesses in the legislation and enforcement.

Enforcement Activity and Legal Dispute Resolution Timeframes

Collectively, metrics were collected on regulatory actions and dispute resolution timelines to evaluate practical application and enforcement (Fig. 2). These indicators are a

measure of the rapidity and frequency with which legal systems react to violations within the smart textile sector, focusing on issues including data privacy violations, negative developments relating to product safety, and IP infringement.

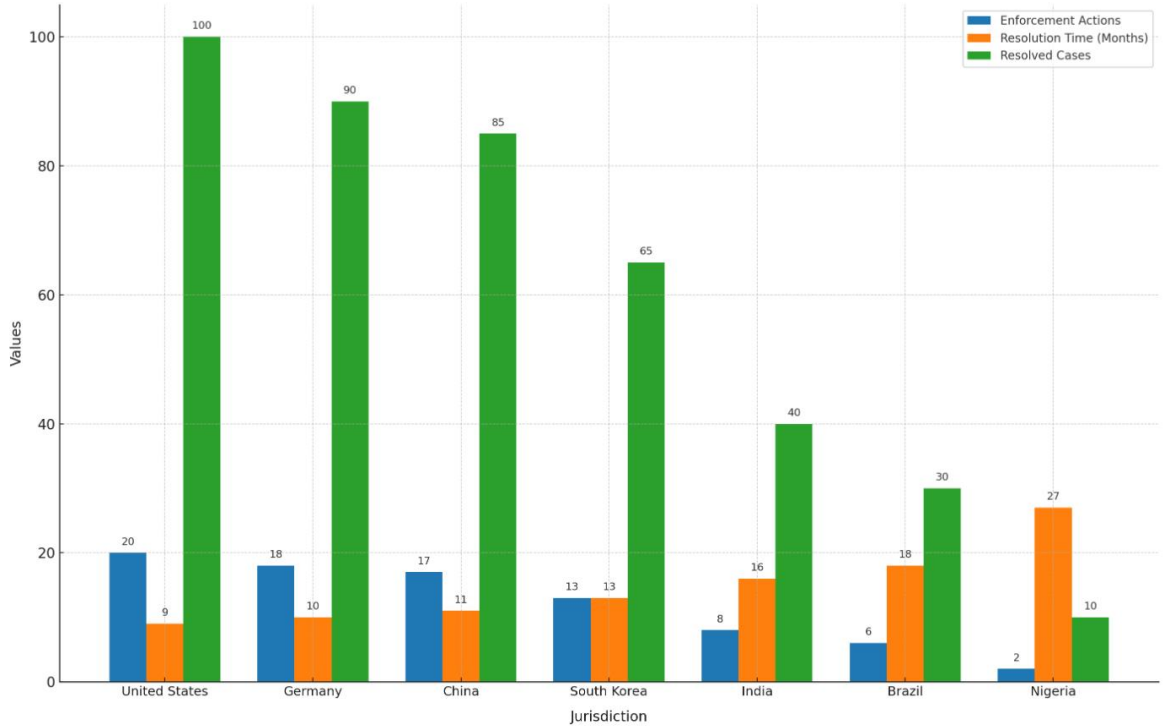

Fig. 2

Fig. 2 represent that United States and Germany had the most annual enforcement activity, which, thanks to short resolutions periods – 9 and 10 months – suggest that both countries have shown operational maturity in handling disputes arising in contexts of wearable technology. Next up are China and South Korea, but the timeline for resolution slogs a bit. India and Brazil have on the contrary higher annual average durations and less masterminded cases handled annually. Nigeria's figures are strikingly low, reflecting both low enforcement capacity and large backlogs in dispute resolution with delays often exceeding two years.

Sectoral Breadth of Regulatory Coverage

Smart textiles are used in various industries from healthcare to sports, supply chain to military. This section explores the extent of regulation as it assesses the number of sectors (table 3) that legally binding instruments cover per jurisdiction.

Table 3

Jurisdiction	Total Smart Textile Regulations	Covered Sectors	Sectors
United States	48	6	Healthcare, Military, Sports, Consumer Wearables, Automotive, Industrial
Germany	42	5	Healthcare, Logistics, Sports, Industrial, Automotive
China	39	6	Healthcare, Military, Public Safety, Smart Cities, Fitness, Retail
Canada	31	4	Healthcare, Sports, Consumer Devices, Defense
India	21	5	Healthcare, Smart Cities, Sports, Agriculture, Logistics
Nigeria	9	3	Consumer Wearables, Agriculture, Healthcare

Jurisdictions such as the USA and China exhibit broad sectoral coverage (including six distinct industries receiving responsive legal treatment) (see Table 3). Germany and Cana-

da also apply multi-sectoral regulation but provide fewer legal texts. So, while India, an emerging-market country, has added five sectors to its legal radar, enforcement is still weak. Nigeria's low numbers are indicative of limited policy development and capacity in dealing with sector-specific regulation.

Intellectual Property Activity and Disputes

In this section, we explore the relationship between the clarity of IP regulation and actual patenting behavior, as well as litigation count and costs.

Table 4

Jurisdiction	Annual Smart Textile Patents	Annual IP Disputes	Avg. Cost per Dispute (USD)	Avg. Time to Resolution (Months)
United States	40	10	$45,000	8
China	38	11	$43,000	9
Germany	35	9	$47,000	10
South Korea	32	7	$50,000	11
India	18	6	$62,000	14
Brazil	14	4	$72,000	16
Nigeria	10	3	$88,000	20+

From the data in Table 4, we see that jurisdictions having clearer cut IP rules (like U.S., China and Germany) end up generating a lot more annual patent filings, and also process more disputes with a relatively lesser amount of money and time involved. Filing less than United Kingdom and USA, relatively high costs of resolving disputes: India, Brazil – significantly less developed than many other jurisdictions, operating with weaker IP enforcement. Nigeria displays the most immature environment, at least as regards protection and resolution of innovation.

Discussion

Results of this study highlight important differences in the existing regulation of smart textiles and wearable technology across the globe. Mature regulatory landscapes in jurisdictions such as the US, Germany, and China show a far stronger performance across all the different legal dimensions – data privacy, IP, product liability, enforcement activity, and consumer protection. In contrast to earlier studies that focused mainly on one crime dimension – such as privacy [13] or liability in the sphere of surgical robotics [15] – this study's comprehensive cross-sectoral analysis offers a new contribution. For example, while Bouderhem [13] focused on data protection challenges in wearable health technologies, she examined neither the intersection of those challenges with intellectual property or cross-sectoral liability provisions. Reflecting Mohamed's [15] study that highlights the legal uncertainties regarding autonomous systems, our findings substantiated that the absence of well-defined liability mechanisms in numerous countries (for instance, India, Brazil, Nigeria) still hinders effective dispute resolution and discourages commercial investments on smart wearables.

Additionally, the differential between enforcement authority and resolution timeframes echo prior work of Feng et al. [18] that analyzed regulatory friction in the global construction industry. Their insights on procedural complexity and uneven oversight become familiar echoes of the patterns uncovered here: Specifically, that jurisdictions with fragmented or under-resourced legal systems are less able to enforce compliance, or resolve legal conflicts emerging in tech domains. This is especially problematic in areas with elevated market demand and low regulatory readiness, as evidenced by our findings in South Asia and certain regions of sub-Saharan Africa.

The outcomes are also aligned with previous results concerning the digital thread concept as referred from Bianchini et al. [14], that underscores the need for end-to-end traceability and regulatory integration in smart product life cycles. The regulatory density we identify across sectors suggests likewise that jurisdictions with more integrated

legal instruments spanning healthcare, defense, fitness, and logistics are better prepared to manage the legal lifecycle of wearable technologies. In this context, given that the United States and China embed legal mechanisms into sector-specific policy frameworks, this results in continuous oversight across the product use case ecosystem.

The fragmentation of policy in emerging economies confirmed Mardasova's analysis [16], summarily stating that there are inconsistencies between emerging technologies and legal presentations and the need for harmonized tax and legal codes. Although there is significant active development in textile innovation, such as energy-harvesting and sensor integrated textiles, Dulal et al. [19] researched of parallel legal development is a major regulatory risk. This aligns with the current study's conclusions: jurisdictions that permit technological innovations without updating their respective legal frameworks tend to experience greater incidence of data breaches and IP disputes, compared to perceived consumer mistrust.

Another area that is worth discussing is the user perception of surveillance and data transparency provided by Campbell et al. [20]. A scoping review on smart home surveillance, by -related to consumer trust, mirrors the findings of the present study and describes limitations to consumer acceptance. Our findings indicate a greater level of user satisfaction and lower incidence of privacy-related litigation in jurisdictions that have comprehensive consumer protection laws (the EU and Canada). In less regulated settings, on the other hand, fears about unauthorized collection of data, as well as non-transparent consent mechanisms, remain high, including, as noted by Kim et al. [17], due to lax laws and enforcement with respect to notification.

This research has also been contextualized within wider health driven discourses around wearables, including those proposed by Kang and Exworthy [21], where they contend that wearables provide the next aesthetic of personalized health where upon settings of a wearer's lifestyle and behavior, wearables will encourage self-empowerment in personal health. But, as our results demonstrate, this empowerment is highly conditional on ensuring sufficient regulatory protections exist. The time is now for the federal government to step in and ensure the protection of consumers based upon best available knowledge and health data [22].

Conclusion

The findings highlight the importance of regulatory harmonization, legal modernization, and capacity-building, especially in jurisdictions that are early on the continuum of legal development.

This study showed how combined and sector-specific legal tools lead to a higher probability for smart textile ecosystems to develop sustainably in those jurisdictions. These jurisdictions reflect greater harmonious alignment in provisions relating to data privacy, intellectual property, liability, and consumer protection. Furthermore, they tend to demonstrate increased enforcement intensity and procedural efficiency, indicating a direct correlation between extensive legal frameworks, compliance outcomes, and innovation potential. In contrast, countries with fragmented or nascent legal regimes have lower levels of legal coherence, slower dispute resolution, regulatory inertia, and therefore higher levels of exposure to legal uncertainty and systemic risk.

It also highlighted the importance of a uniform legal perspective across all application domains, indicating that the comprehensive integration of law not only in national legislation but across different domains, where smart textiles will be used (healthcare, defense, consumer electronics, industrial devices) is essential to guarantee legal coverage in all stages of the product cycle of smart textiles.

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