# A Study on the Sustainable Development Path of the Textile Industry from the Perspectives of Marxism and Law: A Case Study of Functional and Intelligent Textiles

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**ABSTRACT** Functional and intelligent textiles are becoming key enabling platforms for wearable electronics, flexible sensing, and electromagnetic-enabled human–machine interaction, while simultaneously introducing unprecedented challenges for sustainable manufacturing and end-of-life management. Focusing on these emerging engineering materials, this study examines the sustainability of functional and smart textiles through an integrated analytical framework combining Marxist political economy with legal analysis. The research argues that the current production paradigm, characterized by planned obsolescence and cost externalization, systematically amplifies labor exploitation, resource depletion, and environmental burdens throughout the lifecycle of advanced textile products. Particular attention is given to hybrid electronic textiles, where conductive fibers, embedded sensors, and composite material architectures substantially complicate recycling and circular utilization. Existing regulatory instruments, including Extended Producer Responsibility and environmental governance mechanisms, are critically evaluated in terms of their effectiveness in addressing the material complexity and transnational supply chains associated with intelligent textiles. The analysis further demonstrates that technological innovation alone cannot resolve structural sustainability constraints without corresponding transformations in production relations and governance frameworks. By integrating material lifecycle considerations with socio-economic analysis, this study provides a complementary perspective for the sustainable development of next-generation functional textiles and offers conceptual insights into the responsible design and lifecycle management of textile platforms supporting wearable sensing and electromagnetic applications.

**INDEX TERMS** smart textiles, e-textiles, sustainable manufacturing, lifecycle management, wearable sensing

## I. INTRODUCTION

THE textile industry is undergoing a technological transformation, driven by rapid innovation and widespread market adoption of functional and intelligent textiles [1]. These advanced materials encompass a range of products, including antimicrobial sportswear, self-heating jackets, and biometric-sensing garments, representing a significant and rapidly expanding market [2,3]. Market analyses consistently project a compound annual growth rate (CAGR) exceeding 15%, with the global market value anticipated to rise from approximately USD 5.8 billion in 2024 to well over USD 20 billion by the end of the decade [4]. This growth is often heralded as a paradigm of innovation, integrating advancements in material science, electronics, and fashion. However, such narratives of technological progress obscure profound sustainability challenges that risk exacerbating the textile industry's substantial environmental and social footprint [5].

The sustainability crisis associated with these advanced textiles is twofold, resulting in a complex waste problem that current infrastructures are ill-equipped to address. Primarily, most functional textiles are composed of synthetic polymers, which contribute to the pervasive issue of microplastic pollution [6,7]. Additionally, the incorporation of microelectronics—such as sensors, actuators, batteries, and conductive yarns—creates a novel and challenging category of electronic waste (e-waste) [8,9]. This e-waste frequently contains hazardous substances like lead, mercury, and flame retardants, as well as valuable and finite resources such as gold, silver, and cobalt. The deeply integrated nature of these hybrid materials renders separation for recycling technically complex and economically unviable, effectively consigning them to landfill from inception [10].

Academic and policy discourse on textile sustainability has predominantly focused on two domains: technocentric solutions (for example, developing biodegradable polymers or innovative recycling processes) and market-based regulatory interventions (such as circular economy models and eco-labeling schemes) [11]. While these approaches offer value, they typically operate within the existing economic paradigm and seldom interrogate the underlying drivers of unsustainable production and consumption. For instance, lifecycle assessments (LCAs) quantify carbon or water footprints but often overlook the social dimensions of the value chain, including labor conditions and resource equity [12]. Policy discussions rarely engage in a fundamental critique of an economic system predicated on perpetual growth [13]. This paper identifies this omission as a critical gap.

To address this gap, we employ an interdisciplinary framework that integrates Marxist political economy with critical legal analysis to examine the sustainability challenges of functional and intelligent textiles. Our central thesis posits that the unsustainability of this sector is not accidental, but a systemic and logical consequence of the capitalist mode of production. The inherent compulsion for capital accumulation, competitive cost reduction, and the creation of novel consumer desires generates contradictions that cannot be resolved by market-compliant legal frameworks. It is important to clarify that this argument does not suggest capitalism is the sole economic system capable of environmental harm; indeed, twentieth-century state-socialist models, driven by rapid industrialization and production quotas, also resulted in significant ecological catastrophes. However, the specific constellation of problems analyzed herein—namely, the relentless creation of consumer desires through commodity fetishism, the logic of planned obsolescence embedded in smart textiles, and the systemic externalization of social and ecological costs onto the Global South—is uniquely propelled by the logic of capital accumulation. This critique is particularly salient given capitalism's dominance as the global paradigm, revealing why market-based legal frameworks, such as Extended Producer Responsibility (EPR), are inherently insufficient to resolve the contradictions they produce. The contribution of this paper lies in bridging critical theory with a material analysis of a specific, high-tech industry sector, elucidating the deep-seated structural impediments to a sustainable future. The article will first establish its theoretical foundations, proceed with a detailed analysis of the industry's value chain, and finally discuss the profound limitations of current solutions, ultimately arguing for a fundamental paradigm shift.

## II. THEORETICAL FRAMEWORK

### *A. A MARXIST CRITIQUE OF COMMODITY PRODUCTION AND SUSTAINABILITY*

Employing a Marxist theoretical lens provides a robust analytical framework for moving beyond surface-level symptoms to diagnose the structural roots of ecological and social crises [14-16]. This approach is grounded in a materialist conception of history, positing that the organization of production fundamentally shapes a society's relationship with nature and its members. Three interconnected concepts are central to this analysis: the metabolic rift, commodity fetishism, and alienated labor.

The concept of the metabolic rift originates in Marx's critique of nineteenth-century capitalist agriculture, wherein he observed that the shipment of food and fiber from rural areas to urban centers depleted soil nutrients, thereby disrupting vital natural cycles [17]. Contemporary ecological scholars, notably John Bellamy Foster, have expanded this concept to describe a fundamental rupture in the relationship between human society and the natural world under capitalism [18,19]. The logic of capital demands constant expansion and regards nature not as a regenerative system to be stewarded, but as a reservoir of cheap or free inputs for production and a convenient sink for waste [20,21]. The modern textile industry exemplifies this rift: from petroleum extraction for synthetic fibers and extensive water use for cotton cultivation and dyeing, to atmospheric emissions from manufacturing and the disposal of garments in landfills, the entire lifecycle constitutes a linear throughput of resources that disrupts and degrades planetary ecosystems [22]. This ecologically destructive process is socially facilitated by commodity fetishism. Marx argued that, in a market economy, products of labor (commodities) appear to possess intrinsic qualities and value, independent of the human labor and natural processes that produced them [23]. The social relations of production are systematically obscured. For example, a smart shirt is marketed and perceived in terms of its advanced functionalities—such as heart rate monitoring, seamless connectivity, and brand prestige [24]. This "fetish" entirely conceals the global network of human and natural exploitation underpinning its creation: the Congolese miner extracting cobalt for its battery, the Chinese factory worker assembling its microchip under intense pressure, the Bangladeshi garment worker stitching the final product for subsistence wages, and the polluted river downstream from the dyehouse [25-27].

This obfuscation manifests as alienated labor. According to Marx, labor under capitalism is alienated because workers lack control over the production process and the final product [28]. Their creative and productive capacities are reduced to a mere factor of production—a commodity (labor power) to be bought and sold. In the hyper-specialized and fragmented global assembly lines for e-textiles, this alienation is acute. Workers may spend entire days performing a single, repetitive task, such as soldering a component or sewing a seam, with no connection to or understanding of the final "intelligent" product [29]. This process is dehumanizing and fundamentally unsustainable, as it treats individuals as disposable instruments serving the pursuit of endless accumulation.

### *B. LEGAL FRAMEWORKS FOR SUSTAINABLE TEXTILES*

In response to escalating environmental impacts from industrial production, a suite of legal and regulatory frameworks has emerged, particularly in developed economies such as the European Union [30]. These regulations, however, are primarily designed to manage the negative externalities of the prevailing economic system rather than to transform it.

EPR is the most prominent policy instrument in the discourse on sustainable textiles [31,32]. EPR is an environmental protection strategy that extends producers' responsibility for products to the post-consumer stage of their lifecycle [33]. In theory, this creates a financial incentive for producers to engage in "eco-design," making products more durable, repairable, and recyclable [33]. The European Union's Strategy for Sustainable and Circular Textiles has made EPR a central policy, with member states such as France already implementing schemes for textiles, footwear, and household linen [34]. These schemes typically require producers to pay a fee to a Producer Responsibility Organization (PRO), which manages the collection, sorting, and recycling of post-consumer products. Distinctions exist between financial EPR, where producers pay the fee, and physical EPR, where producers are directly involved in take-back and recycling logistics.

Beyond EPR, other regulations constitute a patchwork of environmental governance. The EU's Ecodesign for Sustainable Products Regulation (ESPR) aims to set mandatory minimum standards for product durability, reusability, and recycled content [35]. Chemical regulations, such as REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals), seek to control the use of hazardous substances in products [36]. For intelligent textiles, directives originally designed for conventional electronics are also applicable, including the WEEE (Waste Electrical and Electronic Equipment) Directive, which mandates separate collection and recycling targets for e-waste, and the RoHS (Restriction of Hazardous Substances) Directive, which restricts materials such as lead and cadmium [37].

Despite the appearance of a comprehensive regulatory landscape, critical legal analysis reveals significant gaps and systemic limitations [38]. These regulations are often poorly harmonized, resulting in loopholes. More fundamentally, they operate on the premise that environmental harm can be managed through technical standards and market-based instruments, without challenging the core economic drivers—namely, growth, competition, and consumption—that incentivize unsustainable practices [39]. This paper will analyze how the unique material and social realities of the functional and intelligent textile industry highlight the profound inadequacies of this regulatory approach.

## III. ANALYSIS: CONTRADICTIONS IN THE SUSTAINABILITY OF FUNCTIONAL AND INTELLIGENT TEXTILES

Applying the Marxist and legal frameworks established in the preceding section, this analysis demonstrates how these theoretical concepts are materially manifested throughout the lifecycle of functional and intelligent textiles. Specifically, we trace the metabolic rift in the production chain and deconstruct the commodity fetishism that conceals the system of alienated labor.

### *A. THE METABOLIC RIFT IN ADVANCED TEXTILE MANUFACTURING*

The lifecycle of functional and intelligent textiles exemplifies the metabolic rift, characterized by intensive resource depletion, chemical pollution, and an intractable waste crisis (see Figure 1).

On the input side, the material demands are substantial. The majority of functional sportswear and outdoor gear is composed of synthetic fibers such as polyester and nylon, which constitute over 60% of global fiber production. These fibers are derived from petrochemicals—a non-renewable resource—through energy-intensive polymerization processes. Even "natural" functional fibers, such as merino wool, have significant environmental footprints related to land use and methane emissions from sheep. Functional attributes are often conferred by incorporating finite materials; for example, the demand for silver as an antimicrobial agent in textiles has grown considerably. While the quantity per garment may be small, cumulative extraction exerts substantial environmental pressure, with associated damage from mining activities.

The processing stage further exacerbates ecological disruption. Dyeing and finishing are among the most chemically intensive industrial processes. To achieve properties such as water repellency, manufacturers have historically relied on per- and polyfluoroalkyl substances (PFAS). These "forever chemicals" are highly persistent in the environment, bioaccumulative in wildlife and humans, and associated with serious health risks. Studies consistently detect elevated concentrations of PFAS in water bodies near textile manufacturing zones, confirming the direct discharge of pollutants into ecosystems.

On the output side, the waste problem is twofold. First, there is the continuous, invisible shedding of microplastic fibers during laundering. A single garment can release hundreds of thousands of fibers per wash, which pass through wastewater treatment plants and enter rivers and oceans, ultimately being ingested by marine life and entering the global food chain. Second, the end-of-life disposal crisis is particularly acute for intelligent textiles. According to the Global E-waste Monitor, humanity generated a record 53.6 million metric tons of e-waste in 2019, with less than 18% formally collected and recycled. Smart textiles represent a particularly problematic subset of this stream, as they are composite materials in which electronic components

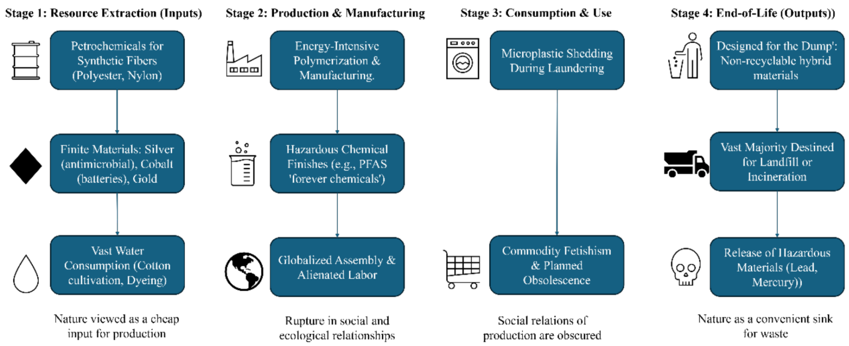


**FIGURE 1.** The Linear Lifecycle of an Intelligent Textile

are laminated, bonded, or woven directly into fabrics. This integration effectively "designs for the dump." Currently, no commercially viable, large-scale technology exists to efficiently separate textile fibers from conductive yarns, sensors, and microcontrollers. Shredding these items contaminates the textile fraction, while manual disassembly is prohibitively labor-intensive. Consequently, most high-tech, resource-intensive garments are destined for landfill or incineration, resulting in the permanent loss of valuable materials and the release of hazardous components, thereby perpetuating a linear production model antithetical to circular economy principles.

### B. ALIENATED LABOR AND VALUE CHAINS IN THE GLOBAL SOUTH

The marketing of intelligent textile products—such as biometric-sensing yoga tops or GPS-enabled running shoes—exemplifies commodity fetishism, presenting products as innovations while concealing their origins in a global network of exploited labor. A deconstruction of the value chain reveals a stark reality of alienation (see Table 1).

The value chain often begins with raw material extraction under harsh conditions. A key component of lithium-ion batteries in wearable devices is cobalt, over 70% of which is mined in the Democratic Republic of Congo (DRC). Human rights organizations have documented the use of child labor and unsafe working conditions in artisanal mines, where miners work for subsistence wages. This situation underscores the limitations of legal frameworks such as the EU's Conflict Minerals Regulation, which, despite good intentions, faces challenges in enforcement and transparency within fragmented and informal supply chains, allowing corporations to evade meaningful accountability.

Subsequently, electronics manufacturing typically occurs in special economic zones in countries such as China, Vietnam, and Taiwan. Labor alienation in these zones is characterized by intense production pressures and Taylorist management. Workers on assembly lines for sensors or microchips perform highly repetitive tasks dictated by machine pace, with documented issues including excessive overtime, high stress, and suppression of independent unions. Here, legal critique reveals "regulatory arbitrage," whereby transnational corporations exploit weak enforcement of labor laws, a structural gap unaddressed by consumer-facing regulations in the Global North.

Finally, electronic components are shipped to garment factories in textile hubs such as Bangladesh, Cambodia, or Ethiopia, where final assembly integrates technology into textiles. This stage combines the pressures of fast fashion—low wages, long hours, hazardous conditions—with the technical demands of handling electronics. Garment workers, often young women, are paid negligible piece rates, alienated from the product, the process, and their colleagues due to intense competition and management strategies discouraging collectivization. This highlights the inadequacy of product-centric regulations like REACH or RoHS; while these frameworks address chemical safety for products sold in Europe, they lack the capacity to enforce labor rights or environmental standards in overseas factories.

The final price of a smart garment—such as $250—reflects these dynamics. The majority of value is captured by intangible assets: brand intellectual property, technology patents, and marketing budgets constructing the commodity's fetishized image. Consumers interact only with this image, disconnected from the alienated labor and metabolic rift embodied in the product.

## IV. DISCUSSION

### A. THE INADEQUACY OF LEGAL REMEDIES WITHIN A CAPITALIST FRAMEWORK

The systemic nature of the challenges analyzed above reveals why current legal and regulatory approaches, although not without merit, are fundamentally insufficient (see Table 2). These frameworks are designed to manage the negative effects of a destructive system, rather than to transform the system itself.

A critical analysis of EPR must recognize its nuances, synthesizing Marxist and legal perspectives to reveal structural limitations. While these frameworks represent a significant policy evolution and may yield incremental benefits—such as funding for improved waste management infrastructure and marginal ecodesign improvements—EPR operates entirely within the capitalist logic of cost-benefit analysis, without challenging the fundamental drive for capital accu-

**TABLE 1.** Deconstruction of a Smart Garment's Value Chain and Alienated Labor

| Component/Stage | Fetishized Attribute (Visible to Consumer) | Underlying Reality (Alienated Labor & Metabolic Rift) | Geographic Locus (Example) |
|---|---|---|---|
| Battery | Long-lasting power for seamless connectivity | Child labor, unsafe artisanal mining for cobalt, resource depletion | Democratic Republic of Congo |
| Microchip/Sensor | Advanced biometric tracking for peak performance | Intense production pressure, repetitive assembly tasks, suppression of unions | Special Economic Zones (e.g., China, Taiwan) |
| Fabric & Dyes | High-performance, water-repellent, antimicrobial fabric | Petrochemical dependency, PFAS pollution, microplastic shedding | Textile Manufacturing Zones |
| Final Assembly | Sleek design, premium brand experience | Subsistence wages (piece rate), long hours, hazardous conditions, no connection to final product | Garment Factories (e.g., Bangladesh, Cambodia) |
| Retail Price: $250 | Symbol of innovation and status | Majority of value captured by intangible assets such as branding and patents, not by labor | Global North Markets |

**TABLE 2.** Critique of Legal Frameworks for Sustainable Intelligent Textiles

| Legal/Regulatory Framework | Intended Purpose | Systemic Limitations & Critical Critique |
|---|---|---|
| EPR | Make producers financially responsible for post-consumer waste, incentivizing eco-design | Functions as a "license to pollute" if fees are less than profits from unsustainable models. Cannot foster circularity where no viable recycling technology exists for e-textiles. Fails to challenge the core imperative of overproduction. |
| ESPR | Set standards for durability, repairability, and modularity | Operates within a paradigm of individual consumerism, promoting "modular obsolescence" (e.g., new replaceable parts annually). Contradicts the market imperative for rapid turnover and growth. |
| WEEE & RoHS Directives | Mandate separate collection of e-waste and restrict specific hazardous substances | While effective for conventional electronics, these directives are largely inapplicable to e-textiles due to the inseparability of electronic and non-electronic components, resulting in continued landfilling or incineration. |
| General Weakness (All Frameworks) | Enforce standards within a specific market (e.g., the EU) | Limited ability to enforce labor and environmental standards in global supply chains. Facilitates "regulatory arbitrage," enabling corporations to relocate production to regions with lax enforcement, externalizing costs onto the Global South. |

mulation. For corporations, EPR fees are calculated business expenses rather than moral or ecological imperatives. When surplus value derived from unsustainable practices outweighs compliance costs, the regulation's deterrent effect is neutralized, reducing EPR to a "license to pollute." For e-textiles, where no scalable recycling technology exists, EPR schemes often fund collection for landfilling or incineration, which falls short of circular economy ideals.

Similarly, the EU's Ecodesign regulation promotes modularity and repairability but remains embedded within a paradigm of individual consumerism. While it may enable smart garments with replaceable electronic components, it does not challenge the imperative to sell updated models annually, perpetuating a stream of "modularly obsolete" components. There is a fundamental contradiction between the goals of eco-design (longevity, durability) and the market imperative of turnover and growth.

Moreover, these regulations are critically limited in the context of global governance. The EU can legislate standards for products sold within its market, but it lacks the authority to enforce labor or environmental standards in overseas factories. Transnational corporations exploit these governance gaps by locating production in regions with weak regulatory enforcement, externalizing social and ecological costs onto communities in the Global South, even as final products comply with standards in the Global North.

### B. TOWARDS A PARADIGM SHIFT: REIMAGINING SUSTAINABLE TEXTILE PRODUCTION

If the problem is systemic, then the solution must be transformative rather than merely technical or incremental. Achieving genuine sustainability requires a paradigm shift that challenges the prevailing logic of the current system. This entails moving beyond the corporate-friendly version of the "circular economy," which is often appropriated as a greenwashing strategy. From a critical perspective, a truly circular material economy is logically incompatible with the requirement for endless exponential economic growth. True circularity likely necessitates a transition toward a "post-growth" or "degrowth" economic model, prioritizing human and ecological well-being over capital accumulation.

In the textile sector, such a shift would redirect focus from producing ever-increasing quantities of new products to a model centered on maintenance, care, repair, and longevity. This could manifest as business models emphasizing product-as-a-service (e.g., clothing rental and subscription services), manufacturersupported repair and take-back programs that treat returned garments as valuable assets for remanufacturing, and thriving local economies built around second-hand sales, swapping, and community mending workshops. Policy levers to support this transition might include tax incentives for repair services, extended warranty mandates, and "right-to-repair" legislation ensuring access to components and manuals for e-textiles. For intelligent textiles, radical design principles would be required: extreme durability, opensource software and hardware, and fully modular components that users can easily replace and upgrade. The business model would shift from selling units to providing services and long-term support.

Realizing such transformation requires agency from multiple sources. Stronger, legally binding international regulations on labor rights and environmental protection are essential and must be impervious to circumvention by transnational corporations. Crucially, grassroots mobilization is necessary. Historical evidence indicates that social change is often driven by collective action. Robust, independent trade unions across textile and electronics supply chains are vital for securing living wages and safe working conditions, challenging labor exploitation. Mobilized consumer movements can reject disposable culture and demand transparency and corporate accountability. Environmental justice movements can continue to highlight the disproportionate burden of industrial pollution borne by marginalized communities.

Exploring alternative ownership models—such as worker-owned cooperatives or community-based enterprises—also offers a pathway away from the singular pursuit of profit. While currently niche, these models demonstrate the feasibility of organizing production around principles of democracy, equity, and ecological stewardship.

## V. CONCLUSION

This paper has demonstrated that, when systematically analyzed through Marxist and critical legal frameworks, the celebrated innovation of functional and intelligent textiles is revealed not as straightforward progress, but as a material embodiment of core social and ecological contradictions inherent in the capitalist mode of production. These advanced materials serve as potent carriers of the profound social and ecological antagonisms of our era. Their lifecycle illustrates a deep metabolic rift, characterized by the depletion of finite resources and the creation of intractable waste streams that fundamentally challenge the notion of circularity. Their value chain is underpinned by a global system of alienated labor, and the "intelligence" presented to consumers is a fetish that obscures the human and environmental costs of production.

This paper has argued that existing legal frameworks, including Extended Producer Responsibility and Ecodesign standards, are structurally incapable of resolving these contradictions. While they may achieve incremental improvements, they function as ameliorative measures within a fundamentally irrational system—addressing symptoms such as waste, pollution, and inefficiency, while leaving untouched the root cause: the relentless drive for capital accumulation through production and consumption. The analysis confirms that sustainability is not a technical challenge awaiting an engineering or policy solution; rather, it is a political and economic issue embedded in the very structure of our economic system.

The principal contribution of this research lies in systematically integrating structural economic critique with material analysis of a cutting-edge technological sector. In doing so, it challenges the textile industry, policymakers, and researchers to move beyond superficial remedies. A truly sustainable and just pathway for the future of textiles necessitates a radical vision—one that subordinates profit to the needs of people and the planet, embraces principles of sufficiency and stewardship, and empowers workers and communities to construct a more democratic and ecologically rational system of production. Recognizing the profound depth of the problem is not a cause for despair, but rather the essential starting point for envisioning and building a transformative future.

## AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analysed during the current stu-d y were available from the corresponding author on reason-a ble request.

## AUTHOR CONTRIBUTIONS

Chenxiang Song and Yuansen Wang designed the study; all authors conducted the study; Chenxiang Song and Yuansen Wang collected and analyzed the data. Chenxiang Song and Yuansen Wang participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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