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Review

A Review of Energy and Sustainability Management in the Fibre-Based Process Industry

Florian Pohlmeyer *, Rosario Othen *, Christian Möbitz and Thomas Gries

Institut für Textiltechnik of RWTH Aachen University, 52074 Aachen, Germany
* Correspondence: florian.pohlmeyer@ita.rwth-aachen.de (F.P.); rosario.othen@ita.rwth-aachen.de (R.O.)

Abstract

This systematic literature review critically examines sustainability challenges and opportunities within fibre-based process industries (e.g., paper and nonwoven), pivotal energy-intensive sectors in the EU. Using an adapted PRISMA guideline, it analyses the evolution of sustainability concepts, key regulatory frameworks (e.g., European Green Deal, Corporate Sustainability Reporting Directive), and established management tools (e.g., ISO 50001, life cycle assessment). The review uncovers critical gaps, including a persistent lack of integrated approaches across environmental, economic, and social dimensions, alongside superficial strategic embedding of sustainability. Furthermore, regulatory fragmentation significantly hinders effective implementation. The study also highlights uneven technology adoption and practical obstacles for circular economy models, largely because sustainability often remains a parallel function rather than a core business driver. Ultimately, transformative sustainability demands integrated, sector-specific strategies, robust data, and strong leadership. This necessitates streamlined regulations, accelerated technology uptake, and enhanced multi-stakeholder collaboration, embedding sustainability into core business models beyond mere compliance.

Keywords: energy management; sustainability; nonwovens; paper industry; circular economy

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1. Introduction

The transition toward sustainable production systems remains one of the most pressing challenges across resource- and energy-intensive industries. Among these, the fibre-based, especially the paper and nonwovens industries play a pivotal role due to their high consumption of raw materials, water, and energy, and their importance for packaging, publishing, hygiene, and technical applications. Although material efficiency and recycling have long been integral to these sectors, particularly in Europe, the accelerating pace of regulatory, ecological, and market developments has intensified the demand for systemic sustainability transformations (Confederation of European Paper Industries, 2020; European Commission, 2020b).

Both industries are characterized by capital-intensive production systems dominated by a limited number of large enterprises. Economies of scale strongly influence cost structures and resource efficiency, while structural and technological constraints limit the flexibility of sustainability improvements. Integrated and non-integrated paper mills differ markedly in energy intensity and raw material sourcing, whereas the nonwovens industry faces additional complexity due to its heterogeneous material base and energy-intensive bonding technologies. As a result, the effectiveness of existing sustain-

ability measures varies widely across firms and value chains (Holik, 2013; Russell, 2022; Stevens & Tuncki, 2019).

1.1. Research Problem

Despite the long-standing efforts in material efficiency and recycling within fibre-based process industries, and the acknowledged need for systemic sustainability transformations, substantial barriers persist. These include the inherent inflexibility stemming from capital-intensive production systems, strong economies of scale, and complex supply chains (Waddock, 2020). While the effectiveness of existing sustainability measures varies, a more fundamental challenge lies in the uncertainty regarding the true impact of current compliance efforts. Specifically, there is an ongoing debate about whether adherence to increasingly stringent frameworks such as the EU Green Deal, the Corporate Sustainability Reporting Directive (CSRD), and the Corporate Sustainability Due Diligence Directive (CSDDD) genuinely leads to transformative environmental outcomes or merely ensures regulatory alignment (Comoli et al., 2023; Schunz, 2022).

1.2. Research Goal

This review aims to provide a structured and comprehensive synthesis of sustainability and energy management concepts in the fibre-based process industries, encompassing both the paper and nonwovens sectors. The review follows a systematic analytical approach, drawing on academic and industrial literature to identify key frameworks, implementation patterns, and emerging trends. It integrates regulatory, technical, and organizational perspectives to map how sustainability strategies are conceptualized and operationalized within this industrial domain. The goal is to derive a coherent overview of the sector's progress, challenges, and opportunities in advancing toward sustainable production systems. The conceptual framework of this review (Figure 1) outlines the interrelations between strategy, policy, market dynamics, technology, and data transparency, which together define the analytical boundaries and thematic focus of the study.

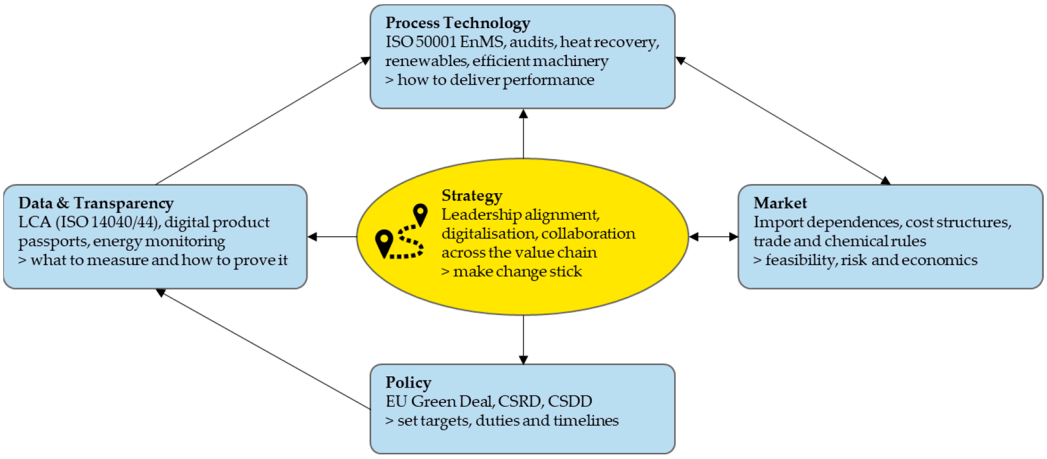

Figure 1. Core topics and relationships of energy and sustainability management in the fibre-based process industry addressed by this literature review.

1.3. Research Methodology

This review adopts a structured literature review methodology, guided by established reporting frameworks like PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), see Figure 2 (Page et al., 2021). The selection and synthesis process integrates both peer-reviewed research and grey literature (industry reports, policy documents, and sustainability disclosures). By systematically comparing conceptual models—such as life cycle assessment (LCA), circular economy frameworks, and energy management

systems (e.g., ISO 50001 (DIN Deutsches Institut für Normung e.V., 2018))—the review identifies the main analytical categories used to assess and improve sustainability performance in fibre-based industries. This methodical approach will enable the resulting synthesis to highlight critical barriers and enablers for the transition toward more resource-efficient, low-carbon industrial practices, while also outlining directions for future research and policy design.

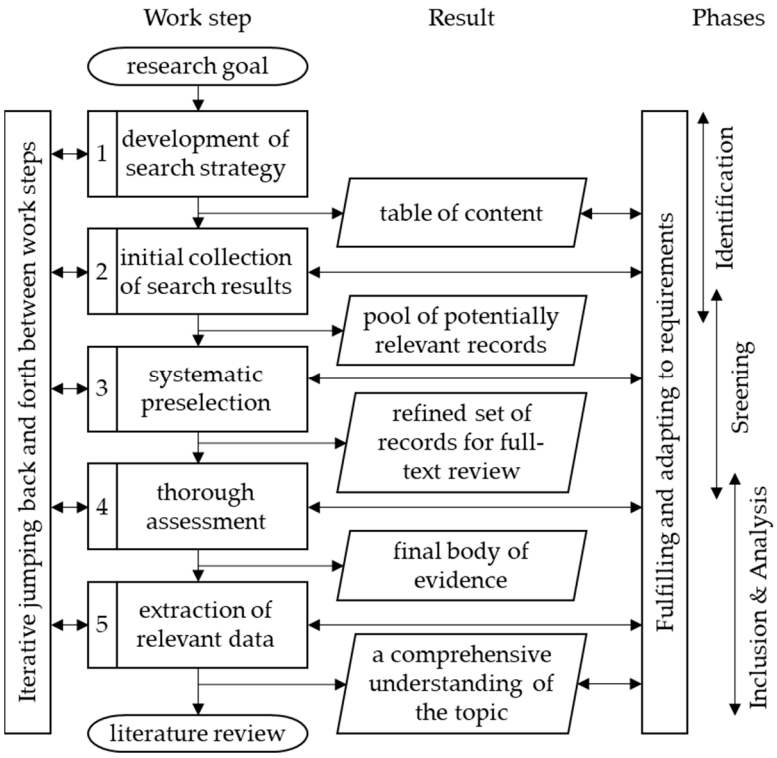

Figure 2. Overview of the Systematic Literature Process, inspired by PRISMA Guidelines.

2. The Evolution and Importance of Sustainability Concepts

The following chapter defines the concept of sustainability and explains the various dimensions.

2.1. Historical Roots of Sustainability

The intellectual roots of sustainability extend back earlier, with significant contributions emerging in the 17th century. John Evelyn, an English naturalist, highlighted critical timber depletion in his seminal work, Sylva, Or A Discourse of Forest-Trees from 1664, urging reforestation and responsible forest management. Concurrently, in France, Jean-Baptiste Colbert's Ordonnance sur les Eaux et Forêts from 1669 established state-led regulations for long-term timber supply. These pioneering efforts in systematic, long-term resource management laid crucial groundwork, directly influencing the more formal articulation of sustainability by Hans Carl von Carlowitz in 18th-century forestry. Carlowitz emphasized using natural resources to ensure their long-term availability, coining the German term "Nachhaltigkeit". This foundational idea laid the groundwork for future definitions of sustainability. Central to his explanation was the notion that present needs must be met without compromising the ability of future generations to meet their own. A needs-based and justice-oriented approach is crucial for adequately addressing the interests of multiple generations and nations (Grober, 2007; Hauff, 2021).

2.2. Three Dimensions of Sustainability

Early sustainability models were primarily ecologically focused, underscoring the necessity of stable ecosystems and the limitation of environmental degradation, following von Carlowitz's rationale. In more recent developments, the concept has expanded to include economic and social dimensions. The economic dimension aims to preserve the foundational structures of economic systems while promoting environmentally and socially responsible growth. Achieving this requires increased production efficiency through technological innovation. The social dimension addresses the fulfilment of individual basic needs, equitable access to essential goods and social resources, and the strengthening of social capital. Social capital encompasses the totality of social networks, trust, values, and norms that promote cooperation within a society. From the recognition of these three core elements emerged the principle of a balanced approach, which formed the basis of the "three-dimensional model" of sustainability presented in Figure 3: ecological, economic, and social (Hauff, 2021).

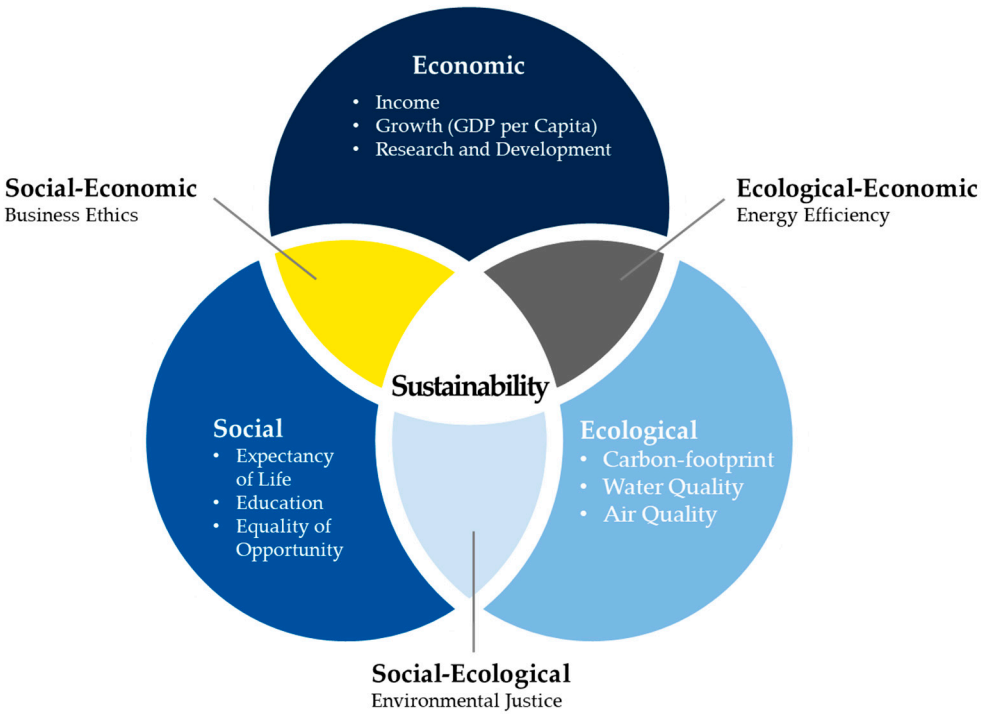

Figure 3. The three dimensions of sustainability by (Hauff, 2021).

3. Regulatory Frameworks for Sustainability in the EU

This chapter outlines the key sustainability- and energy-related regulatory frameworks impacting processing industries, especially the textile industry in Europe and Germany.

3.1. Foundations for Sustainability Frameworks

Most current sustainable development concepts are grounded in the three dimensions of sustainability mentioned above. Notably, the United Nations' Sustainable Development Goals (SDGs) serve as a global framework. The SDGs outline 17 objectives aimed at achieving a sustainable, peaceful, and just world by 2030. These goals integrate social, economic, and environmental aspects (United Nations, 2015).

Another increasingly relevant concept is the Circular Economy. The Ellen MacArthur Foundation first introduced the circular economy framework in 2013, based on principles such as reuse, refurbishing, remanufacturing, and recycling (Ellen MacArthur Foundation, 2013). In 2014, Cramer introduced the "Nine levels of circularity," later expanded into the

10 R's (see Figure 4): Refuse, Reduce, Renew, Re-use, Repair, Refurbish, Remanufacture, Re-purpose, Recycle, and Recover (Council for the Environment and Infrastructure, 2015; Cramer, 2017).

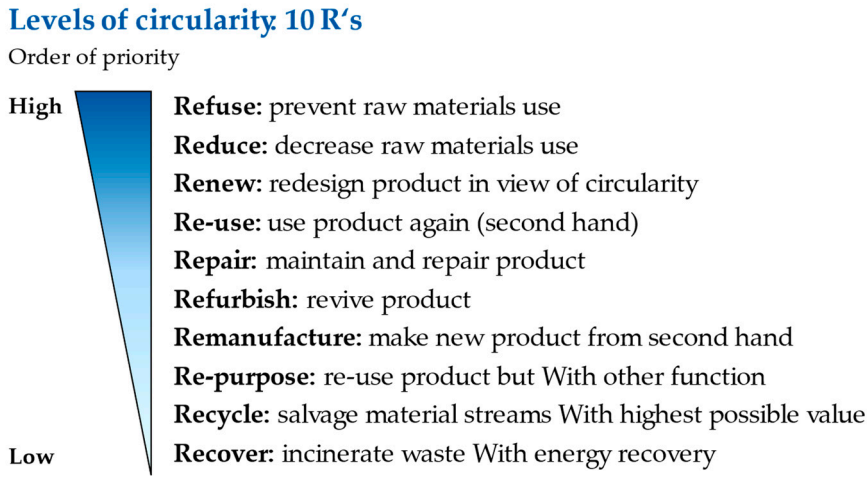

Figure 4. Levels of Circularity: 10 R's. Adapted from (Cramer, 2017).

Applying this framework to the paper and nonwoven sectors reveals a nuanced picture. The paper industry, for instance, has a highly developed recycling system, but faces the material limitation of fibre degradation, which prevents infinite loops and necessitates the input of virgin fibres. This reality underscores the critical importance of moving up the hierarchy towards 'Reduce' (e.g., material lightweighting) and 'Redesign' (e.g., creating products that are easier to de-ink or re-pulp). Similarly, for many single-use non-wovens where recycling is not yet viable, the focus is shifting towards 'Refuse' and developing innovative materials that align with a circular model (Die Papierindustrie e.V., 2025a; Stevens & Tuncki, 2019).

The circular economy aims to establish an environmentally compatible economic system that is in balance with ecosystems (Kadner et al., 2021). Achieving this transformation requires extensive information exchange, standardized data formats to enable traceability and lifecycle transparency, and well- defined circularity criteria and indicators. Achieving these goals depends on cross-sector collaboration throughout the value chain, which can be facilitated through practical demonstrators (Banks, 2017; DIN Deutsches Institut für Normung e.V. et al., 2023).

3.2. Frameworks by the European Union

The European Commission issued two big strategies in recent years: The European Green Deal and the EU Industrial Strategy. Both serve as guidelines for further legislations and aim to advance the European industry in terms of climate neutrality, circular economy, energy transition, digitalisation and raw material supply (European Commission, 2019; European Commission, 2021).

Climate change remains a global priority, with nearly all nations committing under the Paris Agreement to limit global warming to a maximum of 2 °C (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz, 2021). The European Green Deal, illustrated in Figure 5, sets the overarching climate policy vision. It targets net-zero greenhouse gas emissions by 2050 through a comprehensive legislative package. As both a climate policy and a growth strategy, it seeks to decouple economic development from resource use. Key measures address renewable energy, sustainable mobility, building renovation, biodiversity protection, and pollution reduction. These initiatives are supported

by financing instruments such as the Just Transition Mechanism (European Commission, 2019, 2022a).

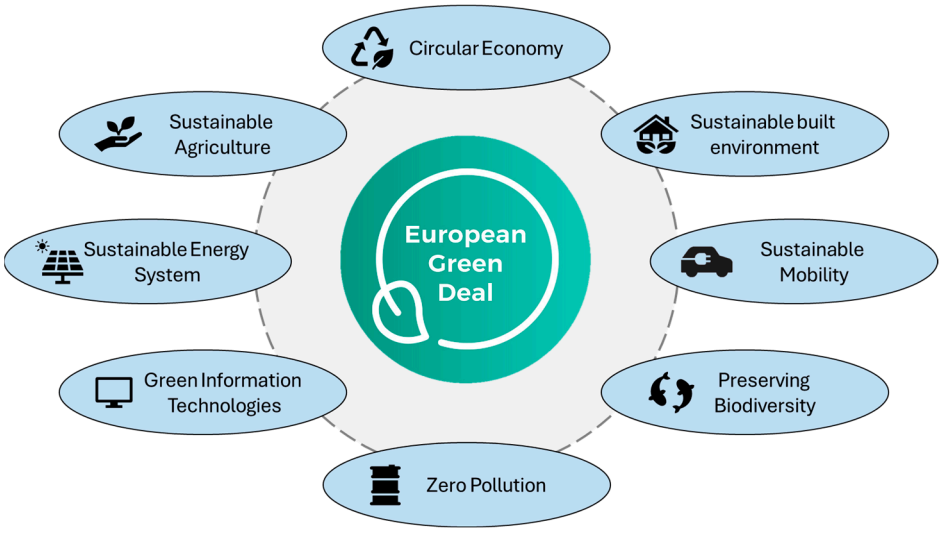

Figure 5. The European Green Deal. Adapted from (European Commission, 2019).

Additionally, the updated EU Industrial Strategy supports the transition to a circular and digital economy by providing the economic policy instruments to realize these goals in an innovative and competitive manner (European Commission, 2021). Key elements include the Chemicals Strategy for Sustainability, the Circular Economy Action Plan, and the strategy for sustainable textiles (European Commission, 2020a).

The Circular Economy Action Plan enhances sustainable product design and expands the EU Ecodesign Directive to more product groups. For textiles, this includes increased utilization of a recyclate, product environmental footprints, and a digital product passport. Consumer empowerment through clear product information and improvements in waste legislation—such as separate collection, extended producer responsibility, and safe recycling—are emphasized (European Commission, 2020a).

The EU Strategy for Sustainable and Circular Textiles promotes durable, recyclable textiles, social rights, and extended producer responsibility. It introduces the Ecodesign Regulation for Textiles, addressing microplastic emissions and mandates a digital product passport. It also emphasizes consumer labelling and promotes circular business models. Implementation involves industry participation in a shared European data space, upskilling, and long-term internationalization of the strategy (Confederation of European Paper Industries, 2025; Die Papierindustrie e.V., 2025a).

3.3. Regulatory Framework and Standards for Energy Management in Germany

Building on the European Green Deal and the EU's broader sustainability targets, national regulations in Germany have intensified the pressure on energy-intensive sectors to implement structured energy management. In this context, industries which are characterized by high thermal energy demand, continuous operation, and large-scale resource uses, are particularly affected by evolving compliance requirements (Bundesministerium für Wirtschaft und Klimaschutz, 2024).

A central legal instrument is the Energy Efficiency Act (EnEfG), which mandates the introduction of certified energy or environmental management systems for companies with an annual final energy consumption above 7.5 GWh. These systems must comply with internationally recognized standards such as DIN EN ISO 50001 (energy management systems) or EMAS (Eco-Management and Audit Scheme). Companies with consumption

above 2.5 GWh, but below 7.5 GWh, are required to conduct regular energy audits and develop energy efficiency action plans (Bundestag, 2023).

Certification under ISO 50001 requires a systematic approach to monitoring, measuring, and improving energy performance, including the definition of clear energy baselines, objectives, and performance indicators. EMAS, while broader in scope, also integrates energy use as a key environmental aspect and involves external validation and public reporting. To obtain certification, companies must undergo independent audits by accredited certification bodies and demonstrate continual improvement (European Parliament & Council of the European Union, 2009; Umweltbundesamt & Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2019).

Additionally, the SpaEfV (Spitzenausgleich-Effizienzsystemverordnung) links eligibility for tax relief on energy products to the existence of such management systems or equivalent alternative systems (e.g., energy audits under DIN EN 16247-1) and measurable efficiency gains (Bundesministerium für Wirtschaft und Technologie, 2020).

Altogether, the legal and normative framework encourages energy-intensive industries not only to meet policy targets but also to realize efficiency gains and cost savings. For example, representatives of the European textile industry have outlined 50 measures that are intended to support the digital and ecological transformation of the fibre-based sector. These measures address sustainable competitiveness, legal frameworks, social responsibility, research and innovation, infrastructure, qualification, investment, and strategic autonomy. A central goal is cross-company data sharing and the identification of practical applications (European Commission, 2023a).

3.4. Corporate Sustainability Reporting and Ecodesign Regulation

The Corporate Sustainability Reporting Directive (CSRD) strengthens mandatory ESG reporting and aims for transparency, comparability, and standardization (European Parliament & Council of the European Union, 2022). Reporting standards are specified in the European Sustainability Reporting Standards (ESRS) (European Commission, 2023b).

The Ecodesign for Sustainable Products Regulation (ESPR) introduces requirements for sustainable product design, prohibits the destruction of unsold goods, and mandates a digital product passport. Data must follow open, interoperable, machine-readable formats (European Commission, 2022b).

New EU rules on textile waste, formulated as the Extended Producer Responsibility (EPR), effective from 2025 on, will require separate waste collection and harmonized extended producer responsibility. Key goals include promoting reuse, enhancing recyclability, and supporting local employment and markets for secondhand textiles (Amt für Veröffentlichungen der Europäischen Union, 2023).

The Corporate Sustainability Due Diligence Directive (CSDDD) obliges companies to identify and mitigate environmental and human rights risks across their entire supply chain. The directive holds executives accountable and emphasizes transparency, recyclability, digital product passports, and data collaboration (Europäische Kommission, 2019; European Commission, 2024).

In Germany, this was implemented through the Supply Chain Due Diligence Act (in German Lieferkettensorgfaltspflichtengesetz, short LkSG). Effective since January 2023, it strengthens rights against child labour, forced labour, discrimination, and environmental violations. Although primarily targeting large enterprises, SMEs are indirectly affected due to cascading obligations. A study by the German Chamber of Industry and Commerce highlights significant challenges in implementation, including bureaucratic burden (93%), unclear requirements (73%), and increased costs (71%) (Seller & Upmeier, 2023).

3.5. Forecast and Sustainability Trends

Despite pandemic-related volatility between 2020 and 2022, segments such as automotive interiors, agriculture, personal care wipes, and cotton pads are projected to grow. A stabilization is expected in hygiene, medical, and filtration markets post-pandemic (Prigneaux, 2024). Sustainability remains particularly challenging in hygiene and medical sectors due to regulatory constraints. Nevertheless, a review of 64 global companies in the diaper and wipe sectors revealed that approximately 70% had integrated sustainable practices, including raw material selection, efficiency improvements, circular economy models, and social responsibility measures. These strategies can be categorized into operational optimization, organizational transformation, and systemic innovation (Table 1) (Rouhento, 2023).

Table 1. Summary of findings from the review of 64 companies categorized by sustainable innovation type (Rouhento, 2023).

Operational Optimization	Organizational Transformation	Systemic Building
Eco-efficiency	New market opportunities	Societal change
• Renewable energy • Closed loop manufacturing • Resource efficiency	• Natural materials • Other renewable materials • Material features (e.g., biodegradability) • Product safety	• Take back system • Product as a service • End-of-life opportunities

4. Market Forces

This chapter analyses the macroeconomic influences illustrated by the example of the fibre-based process industry. A forecast for the future is then discussed by looking at relevant aspects of macroeconomics and economic policy. Figure 6 highlights the key external factors for companies of the fibre-based sector.

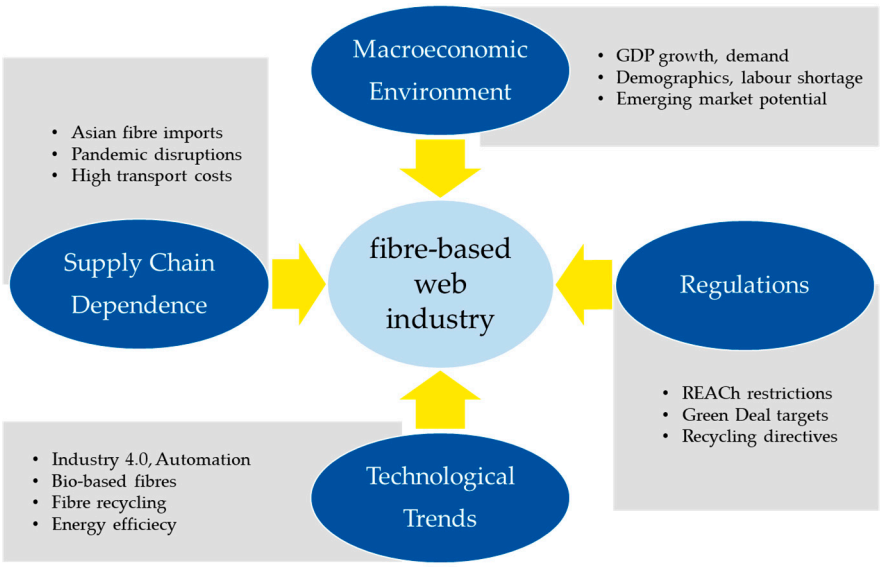

Figure 6. Key external effects on the fibre-based web industry. Adapted from (Osterwalder & Pigneur, 2010).

4.1. Macroeconomic Influences and Structural Challenges

Macroeconomic factors and economic policy strongly affect the nonwoven industry, including indicators like GDP, employment, monetary policy, and trade balances (Meulen et al., 2024). In emerging markets, such as Africa, low per capita consumption of diapers (27.4%) and feminine hygiene products (34.7%) relative to Europe (Statista Market Insights, 2024) suggests significant growth potential (Wiertz & Fuchs, 2012). However, in 2022 the European industry employed 35,939 people (Prigneaux, 2023), and average wages in the textile sector remain substantially below national averages (Statistisches Bundesamt, 2022, 2023). Coupled with demographic shifts, a shortage of skilled workers is anticipated (Fuchs et al., 2021).

4.2. Supply Chains, Regulations, and Bureaucracy

The European man-made fibre industry faces import dependency, especially from Asia, posing challenges for technical textile producers (Veit, 2022). Trade protection measures have been insufficient, sometimes disadvantaging innovation within the EU. While raw materials dominate cost structures, energy costs are increasingly significant. EU chemical regulations, notably REACh (Registration, Evaluation, Authorisation and Restriction of Chemicals), have introduced strict requirements for the use of certain substances, which can limit material availability, increase compliance costs, and in some cases lead to production relocation (European Commission, 2022c).

At the same time, REACh has contributed to a significant reduction in the use and environmental release of hazardous chemicals, thereby improving health and environmental safety. It has also enhanced transparency and information exchange across supply chains—factors that are increasingly important for sustainable production. In certain contexts, the regulation has even driven innovation, as companies are required to substitute restricted substances, particularly when aligned with other regulatory and market pressures. These developments, while challenging, can ultimately support the transition to safer and more sustainable fibre-based production within the EU (Ciatti et al., 2021).

The pandemic highlighted vulnerabilities in global supply chains, prompting a renewed focus on regional production for critical applications such as medical textiles. Despite growing demand for sustainable production, a broader return to domestic textile manufacturing remains unlikely due to high labour costs (Veit, 2022).

Efforts to reduce bureaucratic burdens in the EU and Germany have made progress, but stricter regulations (e.g., climate and CSR policies) continue to strain businesses (Röhl, 2020). Empirical studies affirm that excessive bureaucracy hampers economic performance, while digitalisation offers potential for administrative efficiency (Falck et al., 2024).

4.3. Productivity and Industry Outlook

A study by the Kiel Institute (IfW) identified various factors behind Germany's productivity slowdown, including limited digitalisation effects and demographic changes. Strengthening productivity may require digital transformation (especially in SMEs), education in digital skills, and enhanced labour participation (Bundesfinanzministerium, 2017). Given the capital-intensive nature of the nonwoven industry and high transport costs, significant shifts in global production patterns are unlikely (Wiertz & Fuchs, 2012).

5. Significance for Companies

With this chapter, the relevance of the topic for the industry is emphasized. The section presents the challenges involved in implementing effective sustainability and energy management and strategic approaches to overcome these obstacles.

5.1. Sustainability in Business Strategy

Enterprises, aiming to secure their economic future, often view sustainability implementation as a financial burden. However, long-term success depends on innovation and the strategic alignment of business models with market demands. Sustainable elements are becoming increasingly relevant in the design of efficient business models and high-quality products and services (Hinrichs, 2023).

Adopting a sustainable corporate strategy offers multiple advantages. It enhances long-term competitiveness by enabling early identification of future business opportunities and integrating sustainable alternatives that provide economic and ecological benefits. Furthermore, it strengthens relationships with stakeholders—such as customers and investors—who increasingly consider sustainability in their decisions. Finally, sustainable companies not only meet stakeholder expectations but also comply with regulatory requirements, thereby minimizing legal and reputational risks through early adaptation to sustainability standards (Global Reporting Initiative et al., 2015; Hinrichs, 2023; United Nations, 2015).

5.2. Implementation Challenges

While the implementation of sustainability measures offers various benefits, it also poses significant challenges. Besides evident issues such as limited financial resources and time constraints, less visible obstacles arise. Assessing the ecological and social impacts of production processes requires interdisciplinary expertise and appropriate methodologies to quantify economic benefits. Although costs are immediately apparent, potential savings—such as through reduced material and energy consumption—must be systematically measured. Indirect advantages, such as improved employee motivation or corporate reputation, are difficult to quantify. Moreover, sustainability strategies must adapt continually to evolving regulatory frameworks that internalize environmental costs (Schaltegger, 2005).

The transition towards sustainable practices represents a fundamental transformation process that often meets resistance within organizations. Existing structures and dependencies hinder change, with sustainability measures sometimes perceived as external pressure. Internal barriers—such as weak influence of sustainability departments, conflicting objectives, and the absence of systematic approaches—exacerbate these challenges. Responsibilities are often delegated to middle management or individual staff with limited authority, making negotiation and communication skills vital. Strategic alignment and top-management support are essential for successful integration. Since no universal approach exists, sustainability strategies must be tailored to individual corporate contexts (Holzbaur & Fierke, 2022; Mann et al., 2017; Schaltegger, 2005).

5.3. Standardization and Strategic Gaps

Sustainable development, including relevant legislation and business opportunities, requires time and space for implementation within corporate structures. This is crucial to adapt existing business models to the reality of finite resources (Pinelli & Maiolini, 2017).

To foster sustainable development, national and international bodies have introduced several standards. ISO 9001 targets economic sustainability through quality management, ISO 26000 provides guidance on social responsibility, and the ISO 14000 family offers frameworks for environmental management (see Figure 7) (DIN Deutsches Institut für Normung e.V., 2015a, 2015b, 2020a). ISO 50001 similarly outlines energy management systems (DIN Deutsches Institut für Normung e.V., 2018). However, these standards generally address specific dimensions and fail to capture the full complexity of sustainability. A comprehensive international management system for holistic integration remains absent (Moock, 2024).

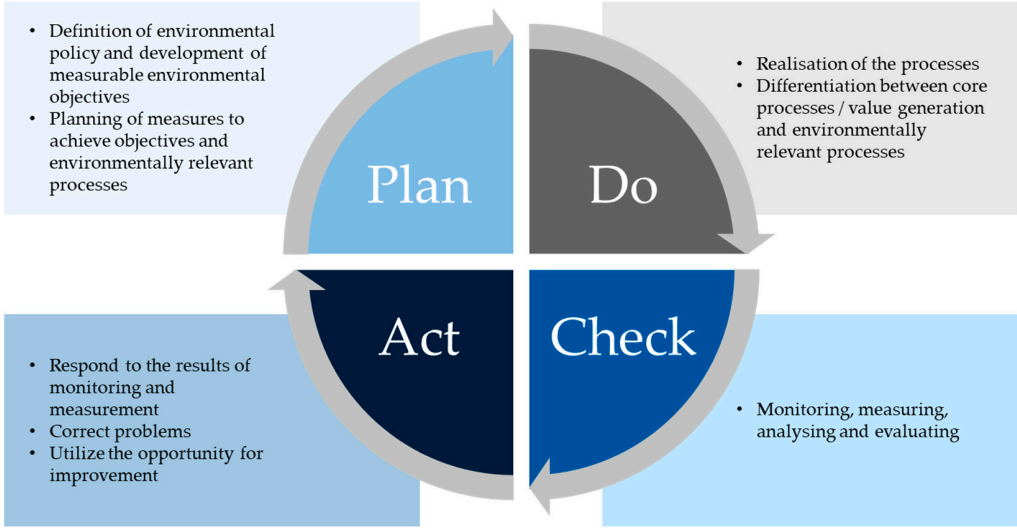

Figure 7. PDCA cycle in the environmental management system according to ISO 14001. Adapted from (DIN Deutsches Institut für Normung e.V., 2020b).

The SDG Compass, developed by the UN Global Compact, the Global Reporting Initiative (GRI), and the World Business Council for Sustainable Development (WBCSD), serves as a framework for embedding sustainability into business strategies (Global Reporting Initiative et al., 2015). It includes status quo analysis, goal-setting, strategy development and implementation, and continuous monitoring (Francisco Bertinetti Lengler et al., 2013; Global Reporting Initiative et al., 2015).

Despite the availability of numerous concepts and guidelines, many companies lack strategic depth in their sustainability agendas, which limits effectiveness (Pinelli & Maiolini, 2017). Research indicates that prioritizing socio-ecological goals mainly based on stakeholder urgency may undermine strategic control and shift the focus toward marketing and public relations rather than substantive transformation (Kurz & Wild, 2015; Pinelli & Maiolini, 2017). To achieve meaningful change, sustainability must be embedded into everyday decision-making processes (Axenbeck et al., 2024).

5.4. Core Topics in Energy Management

Effective energy management is a fundamental component of sustainability strategies in the energy-intensive process industry. The first core topic of this approach is the implementation of Energy Management Systems (EnMS), such as those based on ISO 50001. These systems promote continuous improvement through the PDCA cycle and are often integrated into broader corporate management systems to align energy goals with operational strategies (Javied et al., 2018; Jovanović & Filipović, 2016).

Energy audits are another foundational element, enabling the identification of inefficiencies and untapped savings potential. A key tool in this context is the development of energy performance indicators (EnPIs), such as energy use per ton of product (kWh/t), as well as the establishment of energy baselines (EnBs) to measure progress over time (Umweltbundesamt & BMU).

Digitalization plays a critical role through the deployment of energy monitoring systems, smart metering, and IoT-based automation. These technologies support real-time data collection and are increasingly integrated into higher-level systems such as MES, ERP, and SCADA platforms (Danel et al., 2024).

Finally, the transition to renewable energy, such as biomass, biogas, and solar thermal systems, is gaining importance in the fibre-based sector. This shift not only supports

decarbonization goals but also helps companies reduce reliance on volatile fossil fuel markets (European Commission, 2023a).

6. Methods and Evaluation Concepts

This chapter presents practical tools and methods for implementing sustainability strategies and assessing sustainability performance in industry.

6.1. Sustainability Evaluation and Indicators

Sustainability assessment systems provide the foundation for sustainability information management, including data collection, evaluation, impact analysis, and reporting (see Figure 8). High data quality and transparency of assumptions are essential (DIN Deutsches Institut für Normung e.V. et al., 2023). Most evaluation models emphasize ecological aspects, while economic and social indicators remain underdeveloped (Madreiter & Ansari, 2024).

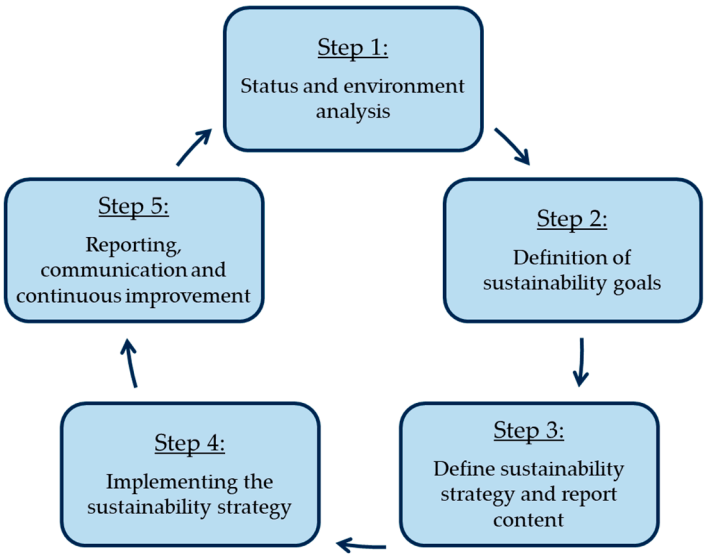

Figure 8. Development of a sustainability strategy. Adapted from (Global Reporting Initiative et al., 2015).

Effective sustainability management requires reliable data on environmental, economic, and social dimensions, measured through key performance indicators (KPIs). Companies should establish KPI systems tailored to their needs. The Global Reporting Initiative (GRI) recommends a materiality analysis to identify relevant KPIs (Wühle, 2022).

The EFFAS publication "KPIs for ESG 3.0" offers a broad set of sector-specific KPIs, including for the textile industry, grouped into Scope I, II, and III categories. These cover environmental ("E"), social ("S"), and economic ("V") dimensions, but need contextual adaptation (Garz et al., 2010).

The Overall Sustainable Equipment Effectiveness (OSEE) model evaluates sustainability in economic, ecological, and social dimensions. Based on the Overall Equipment Effectiveness (OEE) metric from lean management, it extends the traditional performance measures—availability, performance, and quality—with additional sustainability indicators (see Figure 9) (Bertagnolli, 2020; Nakajima, 1988).

The Corporate Sustainability Reporting Directive (CSRD) mandates standardized disclosure of relevant sustainability data across environmental, social, and governance areas, using the European Sustainability Reporting Standards (ESRS) (see Table 2) (European Parliament & Council of the European Union, 2022).

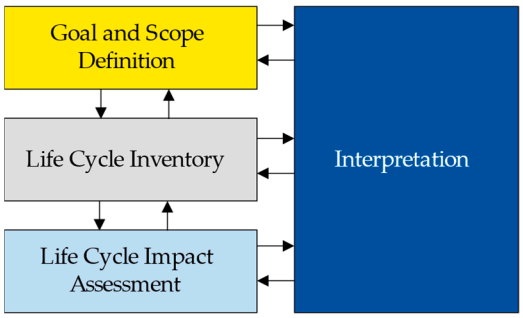

Figure 9. Four steps of the life cycle assessment (LCA) according to ISO 14044. Adapted from (DIN Deutsches Institut für Normung e.V., 2020b).

Table 2. ESRS sustainability indicators according to (European Commission, 2023b).

	Standards	Content
Overarching Standards	ESRS 1: General principles ESRS 2: General information	General requirements and regulatory obligations
Thematic Standards	Environment: E1: Climate change E2: Environmental pollution E3: Water and marine resources E4: Biodiversity and ecosystems E5: Resource use Social: S1: Own workforce S2: Employees in the value chain S3: Affected community S4: Consumers and end users Corporate governance: G1: Business conduct	• Corporate strategy • Corporate objectives • Management of impacts, risks and opportunities • Measuring and target values

6.2. Life Cycle and Environmental Standards

Life Cycle Assessment (LCA) analyses environmental impacts of products, services, or processes across their full life cycle, standardized in ISO 14040/44. The ISO 14000 family offers frameworks for environmental management, particularly (DIN Deutsches Institut für Normung e.V., 2020b):

- ISO 14001: Defines requirements for effective environmental management systems. Therefore it promotes continual improvement, efficient resource use and regulatory compliance (DIN Deutsches Institut für Normung e.V., 2015b).
- ISO 14060: Integrates environmental considerations into strategic planning (DIN Deutsches Institut für Normung e.V., 2019a).
- ISO 14067: Guides the quantification and communication of product carbon footprints by providing a consistent framework for carbon footprint accounting and reporting (DIN Deutsches Institut für Normung e.V., 2019a)

Figure 10 illustrates the ISO 14060 series structure for greenhouse gas (GHG) accounting, including ISO 14064 (GHG inventories and projects), ISO 14067 (product carbon footprints), and ISO 14064-3 (verification). Verification institutions follow ISO 14065 and ISO 14066 standards (ISO 14067).

ISO 50001 supports organizations in improving energy efficiency, consumption, and performance. It facilitates energy policy development, goal setting, and action planning, thereby lowering energy costs and reducing GHG emissions (DIN Deutsches Institut für Normung e.V., 2018).

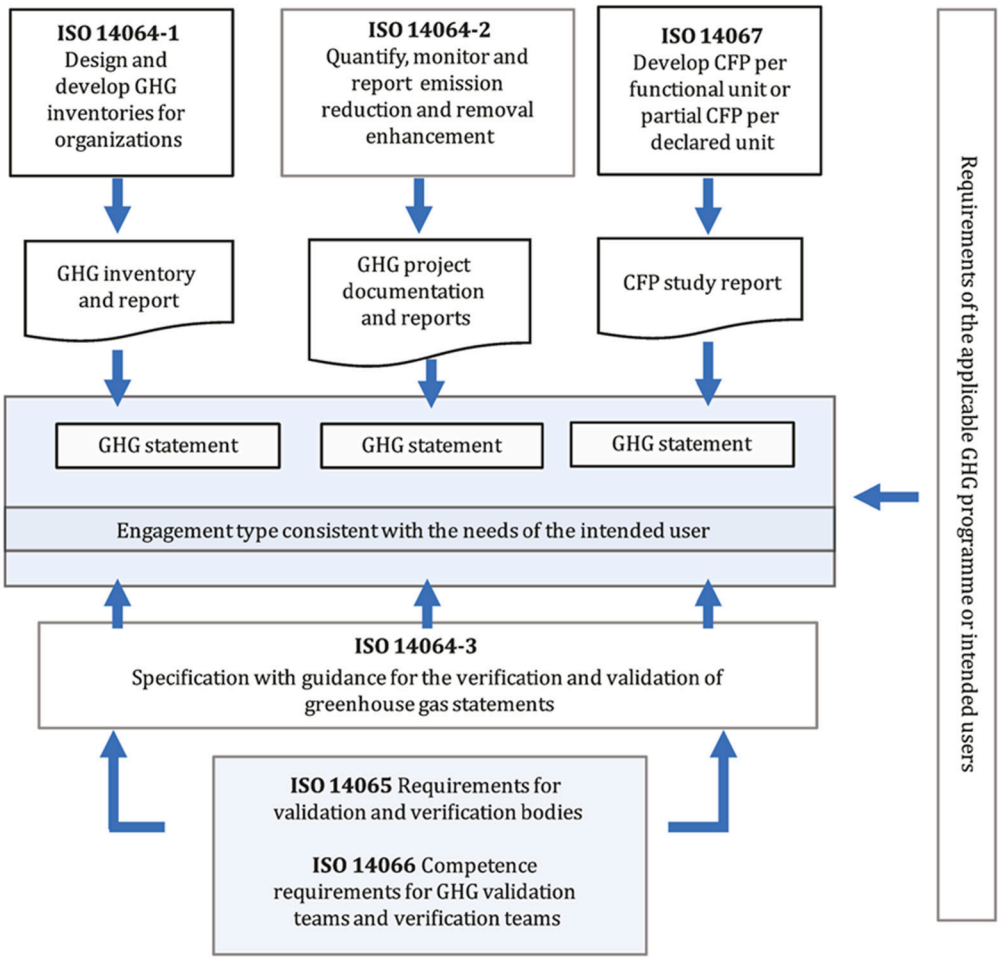

Figure 10. Relationships within the GHG Standards Series ISO 14060 (ISO 14067).

LCA follows four key steps: goal definition, inventory analysis, impact assessment, and interpretation (see Figure 11).

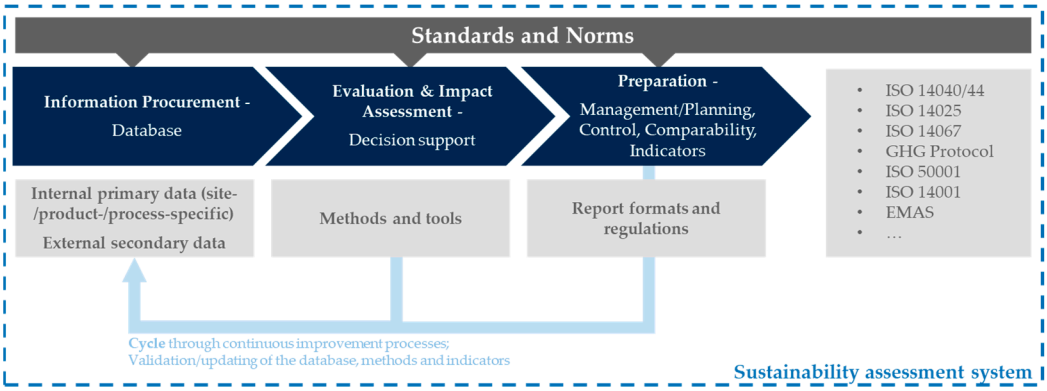

Figure 11. Development of sustainability assessment systems (DIN Deutsches Institut für Normung e.V. et al., 2023).

In order to have a common definition in all member states what a company can market as an eco-friendly product, the European Commission proposes two methods which are in accordance with the Life Cycle Assessment (LCA): The Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF).

The Joint Research Centre (JRC) is the driving force in generating and enhancing the Environmental Footprints (EF). Since 2019 an ongoing transition phase persists, with the primary objectives of:

- establishing a framework for monitoring the implementation of existing Product Environmental Footprint Category Rules (PEFCRs) and Organisation Environmental Footprint Sector Rules (OEFSRs),
- developing new PEFCRs and OEFSRs and
- advancing methodological developments (Directorate-General for Communication of the European Comission, 2025).

6.3. Greenhouse Gas Accounting

GHG balances apply to both organizations and products. The ISO 1406x series, particularly ISO 14064, defines standards for planning, quantifying, reporting, and verifying GHG emissions at the organizational level (DIN Deutsches Institut für Normung e.V., 2019b). ISO 14069 provides additional guidance for enhancing transparency (ISO International Organization for Standardization, 2013), while ISO 14067 focuses on product-level carbon footprints (DIN Deutsches Institut für Normung e.V., 2019a). ISO 14068 aims to prevent greenwashing by promoting transparency in GHG neutrality claims (ISO International Organization for Standardization, 2023).

The Corporate Carbon Footprint (CCF, see Figure 12) measures the total GHG-emissions caused by all activities of an organization. These emissions are categorized by the GHG Protocol–Corporate Accounting and Reporting Standard and ISO 14064 as:

- Scope 1: Direct emissions from owned or controlled sources,
- Scope 2: Indirect emissions from purchased energy,
- Scope 3: Other indirect emissions, e.g., from travel, waste, or procurement (World Business Council for Sustainable Development & World Resources Institute, 2004).

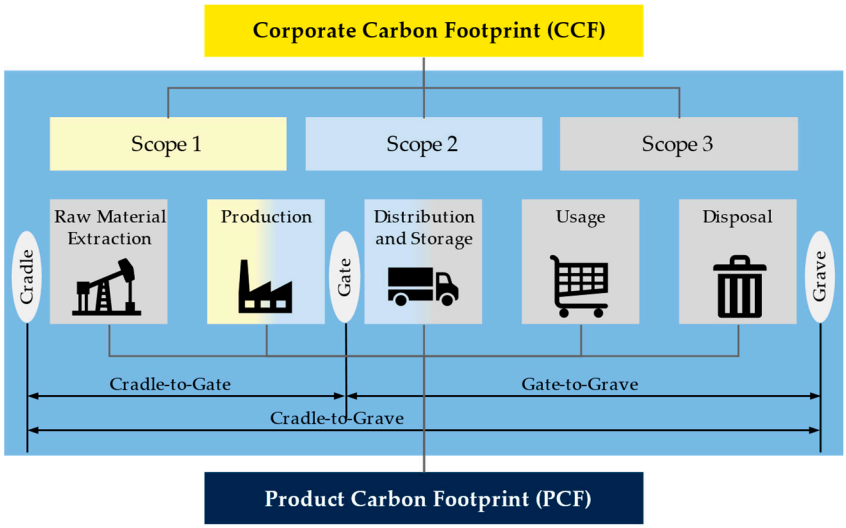

Figure 12. Carbon Footprint Models: Corporate (CCF) and Product (PCF) based on (Enit Energy IT Systems GmbH, 2025; Kleinekorte et al., 2020).

The Product Carbon Footprint (PCF) measures the total GHG emissions generated across the life cycle of a specific product. The life cycle can be defined either as "cradle-to-grave" for the full life cycle or "cradle-to-gate" for the products emissions before shipping (see Figure 12). Key frameworks for PCF include ISO 14067 and the GHG Protocol–Product Life Cycle Accounting and Reporting Standard, which define life cycle stages, system boundaries, and data requirements.

7. Sustainability in the Nonwoven and Paper Industry

This section provides an overview of the current state of sustainability within the nonwoven and paper production sectors, focusing on production processes, supply chains, and key stakeholders. Firstly, the market segments are introduced. Then the manufacturing processes are presented shortly.

7.1. Nonwoven Products and Market Shares

Nonwovens are fibrous webs bonded through physical or chemical processes, excluding woven, knitted, or paper-based products (DIN Deutsches Institut für Normung e.V., 2019c). In Europe in 2024, key applications by production weight include:

- hygiene products (27%),
- wipes (20%),
- construction (16%),
- home and office (10%) and
- filtration (6%).
- (Prigneaux, 2025)

Raw material sources for nonwovens include:

- natural fibres (e.g., cotton, flax),
- synthetic fibres (e.g., polyester, polypropylene),
- fluff pulp and
- polymer powders or granulates.
- (Mieck et al., 2012).

Polypropylene (35.4% overall) and polyester (34.5% of fibre-based) are the most widely used materials in the European nonwoven industry consumption (Prigneaux, 2025).

Table 3 provides an overview of the market shares, sales volumes, and growth or decline up to 2022, alongside forecasts for future development. These figures underscore the heterogeneity of the market and the varying technical requirements among application areas (Prigneaux, 2023).

Table 3. Market shares, growth and decline of product segments in the nonwoven industry (Prigneaux, 2025).

Type of Product	Market Share 2024 [%]		Growth by Segment (2024 vs. 2023) [%]	
	By Weight	By Surface Area	By Weight	By Surface Area
Hygiene products	27.0	56.1	1.7	4.0
Wipes	20.4	15.2	3.4	1.6
Construction	15.8	6.0	9.5	24.4
Home and office	10.2	5.0	−2.5	−14.0
Filtration	6.3	4.8	1	0
Transportation	4.4	1.3	−4.0	−7.7
Medical	3.4	3.2	−0.9	1.1
Agriculture	2.0	2.7	0.3	−2.4
Other	10.5	5.7	15.5	42.0

Markets for absorbent hygiene products, wipes, and transportation remained stable (fluctuations < 5%), largely relying on extrusion nonwovens, airlaid short fibre nonwovens, and hydroentangled or needlepunched materials. Home and office textiles (notably table linen) and packaging displayed moderate growth. In contrast, segments such as medical textiles, filtration, geotextiles, and apparel showed declining trends, with the spike in medi-

cal product demand during the COVID-19 pandemic largely receding. Notably, European demand for nonwoven medical textiles still exceeds domestic production (Prigneaux, 2023).

The nonwoven industry involves a wide range of actors:

- raw material suppliers,
- machinery manufacturers,
- producers,
- converters,
- end users,
- research institutions and
- associations (Stevens & Tuncki, 2019).

Raw materials are mainly imported, with China producing 72% of global synthetic fibres, while Europe contributes just 5% (The Fiber Year Consulting GmbH, 2023; Veit, 2022).

Europe hosts 307 nonwoven producers employing 35,939 people. However, 40 companies dominate 90% of global nonwoven revenues (Wilson, 2022). Many businesses are vertically integrated, serving diverse markets like hygiene and automotive (Prigneaux, 2023).

In Germany, the nonwoven industry lacks a dedicated association and is instead organized under the Gesamtverband der deutschen Textil- und Modeindustrie e.V. (Stevens & Tuncki, 2019). Market structure is mixed, featuring multinationals such as DuPont, Berry Global, and Freudenberg alongside numerous SMEs serving niche segments (Mordor Intelligence, 2024).

The production chain, illustrated in Figure 13, involves four stages:

1. raw material preparation (fibre or granulate processing),
2. web formation,
3. web bonding and
4. finishing (Schlichter et al., 2012; Wiertz & Fuchs, 2012).

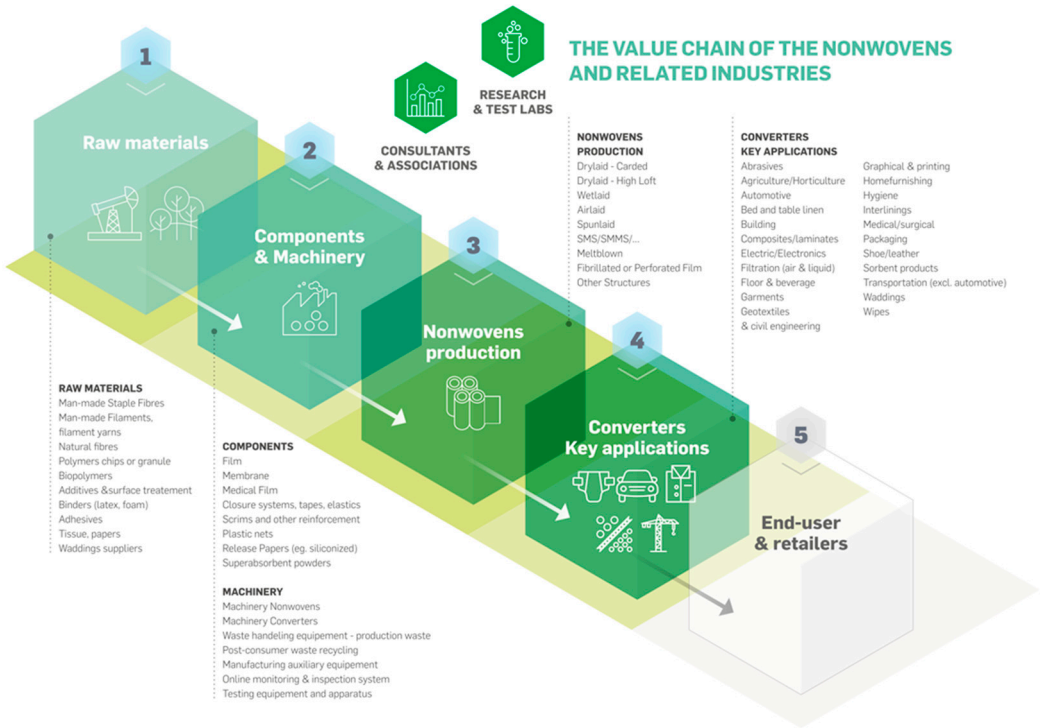

Figure 13. The Value Chain of Nonwoven Industry (Stevens & Tuncki, 2019).

The final stage involves converting nonwovens into products (e.g., composites) (Wiertz & Fuchs, 2012).

In 2024, Europe produced 2.98 million tons of nonwovens, generating €11.83 billion in revenue, with Germany contributing 576,800 tons (Prigneaux, 2025). Despite steady growth, industry profitability remains low (Grebe, 2014; Wiertz & Fuchs, 2012). In 2024, the raw material demand was 3.27 million tons, with 56.76% being staple fibres and pulp (Prigneaux, 2025). Renewable or recycled inputs account for roughly one-third of all raw materials (Prigneaux, 2025; Stevens & Tuncki, 2019).

7.2. Paper Products and Market Shares

The paper industry is dominated by a few large companies operating capital-intensive production facilities. This is due to economies of scale, which improve energy efficiency. The sector includes both integrated and non-integrated mills. Integrated pulp and paper mills perform both pulp and paper production at the same site, while non-integrated mills use externally sourced pulp (Schimmel, 2020; Umwelt Bundesamt, 2000).

In 2023, the German paper and pulp industry saw a sharp decline in production and revenue. Total production fell by about 14% to 18.6 million tonnes, the lowest level in 20 years. Revenue dropped even further—by 27%—to €15.5 billion. This downward trend stabilized in 2024, with revenues falling by only 2.7% and production increasing again by 3.0% to 19.2 million tonnes (Die Papierindustrie e.V., 2024, 2025a).

Despite these declines, Germany remains a major player in the global paper market, ranking fifth worldwide after China, the United States, Japan and India (Die Papierindustrie e.V., 2025a). In 2023, global paper industry output amounted to roughly USD 905 billion. Projections for 2028 suggest an increase to USD 974 billion, representing a growth of 6.6% from 2023 (Bundesministerium für Wirtschaft und Klimaschutz, 2025; Die Papierindustrie e.V., 2025b).

Germany is also highly integrated into international trade on both the export and import sides. Nearly half of the paper, cardboard, and packaging materials produced domestically are exported. In 2024, exports reached 12.2 million tonnes. That same year, the German paper industry employed around 37,000 people. The rate of recycled paper use was notably high, accounting for 84% of raw material input in 2024 (Bundesministerium für Wirtschaft und Klimaschutz, 2025; Die Papierindustrie e.V., 2025a, 2025b).

The European paper industry also experienced a sharp production decline in 2023 but is recovering quickly in 2024 (see Table 4). The distribution of product types is comparable to that in Germany.

Table 4. Market shares, growth and decline of product segments in the European paper and board industry for 2024 (Confederation of European Paper Industries, 2025).

Type of Product	Production Share 2024 (by Weight) [%]	Growth by Segment (2024 vs. 2023) [%]
Containerboard	41.1	4.5
Packaging and wrapping	21.8	11.2
Printing and writing	18.6	4.9
Tissue	10.5	5.6
Newsprint	3.5	−1.8
Other	4.6	5.6
Total	78,742,000 t	5.9

Paper production begins with fibre raw materials—virgin pulp or recovered paper—which are processed, formed, pressed, and dried before optional finishing steps. Main fibre sources include mechanical pulp, chemical pulp, and recycled paper. Modern paper machines, often over 200 m long, are highly complex systems featuring up to 20,000 sensors and 2000 control loops. Their primary function is to remove water from the fibre slurry to

form a cohesive web, which may be coated inline for enhanced print quality. Core sections include stock preparation, forming, pressing, drying, coating, and winding (Blechschmidt, 2021; Holik, 2013).

7.3. Strategies and Challenges

The European Disposables and Nonwovens Association (EDANA) has identified key sustainability priorities: sustainable supply chain, eco-efficiency, building trust and responsible end-of-life (see Figure 14). Sustainability awareness has grown steadily since 2009, driven by customer expectations. Approximately 38% of members adhere to ISO 50001, and over half have CO_2-reduction targets averaging 3.3% annually. Most companies report sustainability efforts through websites, reports, or product labels; 60% provide product-level environmental information (Stevens & Tuncki, 2019). However, it should be noted that environmental information often rely on estimations and assumptions, which can introduce significant uncertainties into the reported figures (Barahmand & Eikeland, 2022; Clift & Druckman, 2016).

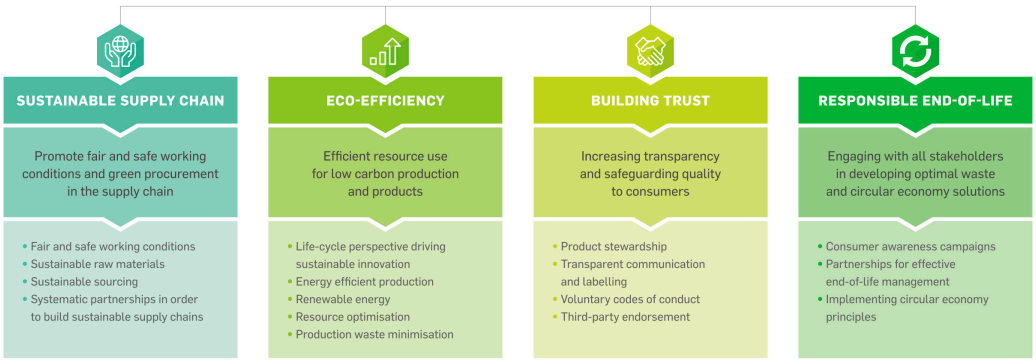

Figure 14. EDANA's Sustainability Vision 2030 (Stevens & Tuncki, 2019).

Major challenges include balancing growth with reduced environmental impact, improving lifecycle performance, enhancing supply chain transparency, meeting regulatory demands, and addressing issues such as single-use plastics and hazardous substances (Stevens & Tuncki, 2019).

7.4. Materials, Processes and End-of-Life

Material use accounts for ~85% of the product's carbon footprint and represents the largest cost factor (Prigneaux, 2024; TWE GmbH & Co. KG, 2023). Common materials remain fossil-based polymers such as polypropylene and polyethylene. However, the statistics on recycled content require careful interpretation. While a significant portion of materials like polyester staple fibres (35%) and granules for spunmelt polyester (40%) are derived from recycled sources (Prigneaux, 2024), this predominantly represents an open-loop system where post-consumer PET bottles are downcycled into fibres ("bottle-to-fibre"). True fibre-to-fibre recycling of post-consumer nonwovens is minimal, with rates estimated to be below 2% (Ellen MacArthur Foundation, 2017; Textile Exchange, 2023). Key challenges hindering a closed loop include the prevalence of multi-material compositions, which are difficult to separate, and the contamination of single-use hygiene and medical products, which are typically excluded from recycling streams. Although the reuse of recycled fibres is increasing (Alves et al., 2024), transitioning to bio-based materials remains challenging due to costs and complex production processes (Giungato et al., 2024). Natural fibres represent about 2% of inputs with no significant growth (Prigneaux, 2024).

Sustainable production efforts focus on energy-efficient machinery and fibre processing (McIntyre, 2022; Stevens & Tuncki, 2019). Nonwoven production generally has

higher energy demands than other textile methods (Kır et al., 2024). Water-intensive processes like wet-laid and hydroentanglement methods offer potential for resource savings. Overproduction is minimal, with 98.8% of output sold (Prigneaux, 2024).

Sustainability is strongly influenced by product design. Average basis weights are declining, improving material efficiency (Stevens & Tuncki, 2019). In many cases, nonwovens have replaced materials with higher environmental impacts (Goswami & O'Haire, 2016). However, their predominant use in disposable products—many for single-use hygiene or medical applications—not only contributes to municipal solid waste (2–6%) but also represents a primary barrier to the fibre-to-fibre recycling discussed earlier (McIntyre, 2024; Stevens & Tuncki, 2019). Key recycling enablers include better material separation and partnerships across the value chain (McIntyre, 2021, 2024; Stevens & Tuncki, 2019). Localized sales reduce transportation emissions (Prigneaux, 2024).

Due to the sector's diversity, sustainability assessments are complex (Kır et al., 2024). Transparency and comparability in sustainability communication are essential (Stevens, 2018), and a holistic view beyond isolated indicators is required (Goswami & O'Haire, 2016).

7.5. Paper Industry Energy Trends

The German paper industry is a major energy consumer. As illustrated in Figure 15, its specific energy consumption dropped from 8242 kWh/t in 1955 to around 2647 kWh/t in 2001 through continuous efficiency improvements (Bayerisches Landesamt für Umweltschutz, 2003).

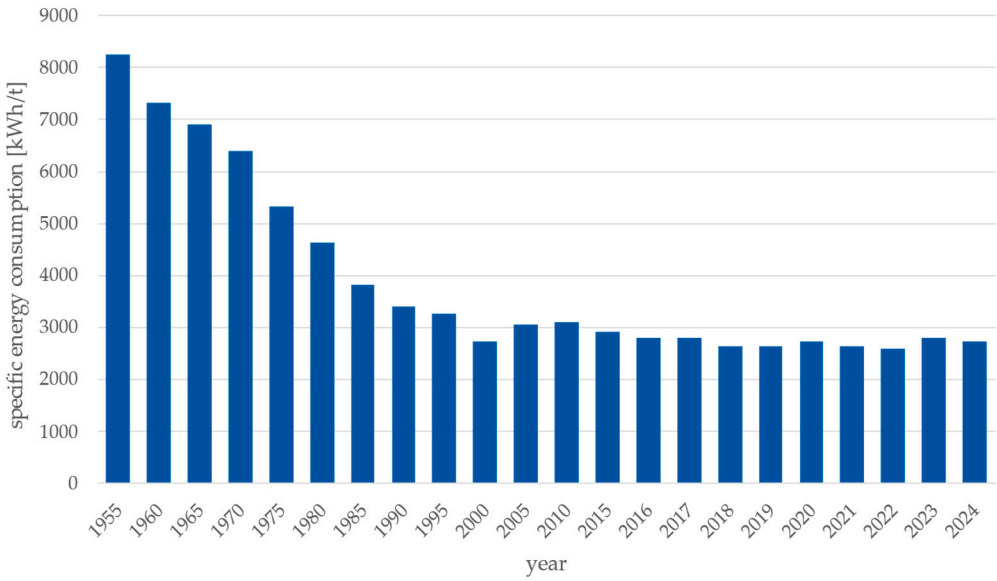

Figure 15. Specific energy consumption of the German paper industry from 1955 to 2024. Data from (Die Papierindustrie e.V., 2025a).

The decline in the specific energy demand of the paper industry is primarily attributed to the development of more energy-efficient machinery and processes. Additionally, a shift towards renewable energy sources, such as biomass and wind power, as well as the integration of waste heat utilization and heat recovery systems, have contributed significantly to energy savings (Bayerisches Landesamt für Umweltschutz, 2003).

Key technologies responsible for reducing specific energy consumption include:

- Advanced press section technologies (e.g., shoe press),
- Higher-efficiency machinery,
- Increased use of recycled paper.
- (Bayerisches Landesamt für Umweltschutz, 2003).

Since CO_2 accounts for 84% of all greenhouse gases, emissions are commonly expressed in CO_2 equivalents for comparability. In Germany, the industrial sector contributes approximately 24% to total CO_2 emissions (Rüger & Buchheim, 2021), with the paper industry accounting for about 4% of these (see Figure 16) (Deutsche Emissionshandelsstelle im Umweltbundesamt, 2021).

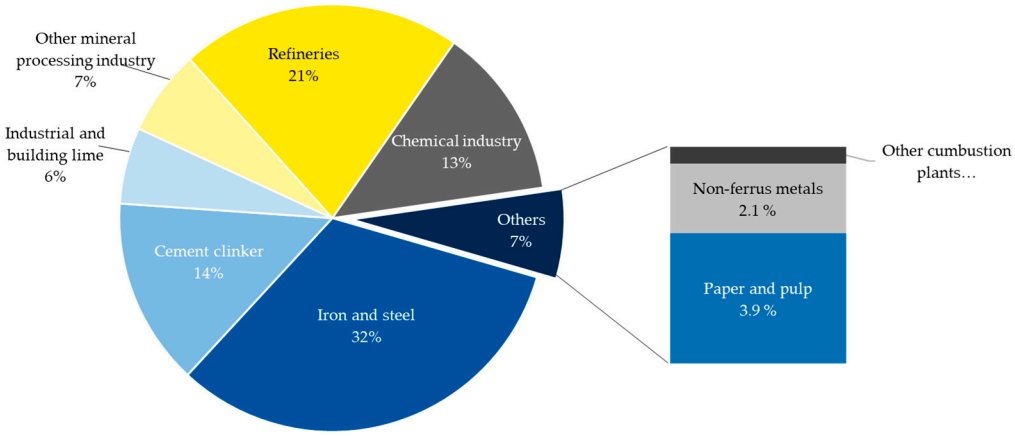

Figure 16. Proportions of individual industries' emissions in the industrial sector in 2024. Adapted from (Deutsche Emissionshandelsstelle im Umweltbundesamt, 2025).

In 2024, the German paper industry reported a specific energy demand of 2724 kWh/t, with over 80% allocated to thermal energy (steam) (Die Papierindustrie e.V., 2025a). Meanwhile the European paper industry reported a primary energy consumption of 3750 kWh/t with approximately 75% allocated to thermal energy. Further details on energy distribution by paper type are found in Table 5.

Table 5. Specific electrical and thermal energy requirement of diverse types of paper (Suhr et al., 2015).

Type of Pulp/Paper	Specific Energy Consumption	
	Power [kWh/t]	Heat [kWh/t]
wood-containing paper	1200–2100	1000–2100
coated wood-free paper	600–1000	1200–2100
wood-free speciality paper	600–3000	1600–4500
recycled packaging paper	300–700	1100–1800
recycled graphic paper	900–1400	100–1600
recycled tissue	800–2000	1900–2800

Energy costs constitute about 18–20% of the total production cost (Pathak & Sharma, 2023). Within the dewatering process, the drying section is the most cost-intensive, responsible for 78% of these costs, followed by the press (12%) and forming sections (10%). The drying section also dominates the machine design, accounting for two-thirds of its length, 50–60% of its mass, and 40% of its capital cost (Ghodbanan et al., 2015).

Quantifying electrical energy use is complex due to the variety of components involved, including drives, pumps, mixers, and vacuum systems, particularly in the forming, press, and drying sections. The energy-intensive drives for up to 100 steel cylinders (each weighing up to 12,000 kg) require precise control to prevent paper web breakage (Michael & Safacas, 2003).

Thermal energy, predominantly in the form of steam, is mainly used in the drying section. Steam is generated on-site, distributed via pipelines, and partially recovered through condensate return and heat exchangers (Othen et al., 2023).

Modern systems include insulated and sealed hoods with air temperatures exceeding 60 °C. These are designed to reuse exhaust heat to preheat incoming air. Heat recovery systems (see Figure 17) aim to replace fresh steam through waste heat utilization, supported by heat pumps. Due to the inefficiency of air-to-air exchangers, waste heat is often used to heat process water (Blechschmidt, 2021).

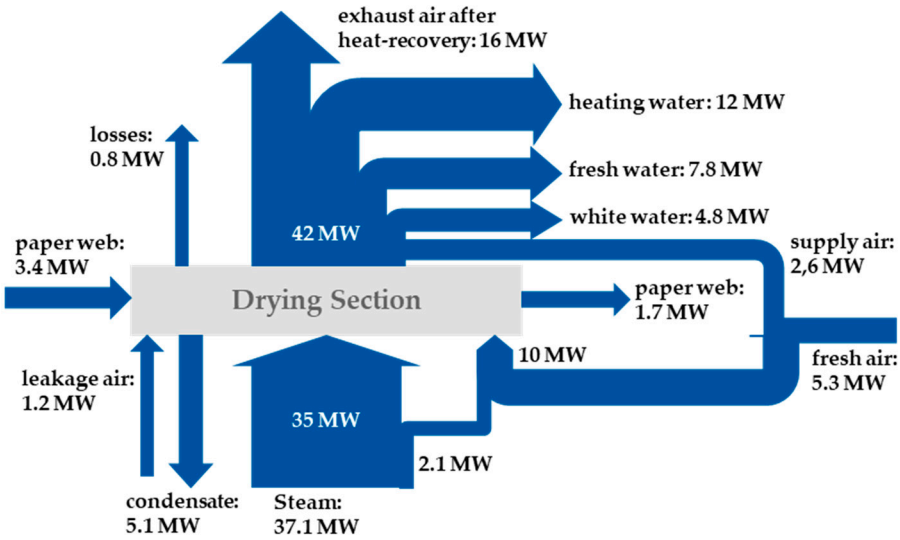

Figure 17. Sankey diagram of the heat flows in a four-stage heat recovery system (Naujock & Blechschmidt, 2021).

Heat recovery can significantly reduce energy demand. One field study across three paper mills identified a saving potential of up to 361 kWh/t from implementing optimized heat recovery, corresponding to 15% of total primary energy use (Laurijssen et al., 2010). More recent models suggest savings up to 30% (Diaconescu et al., 2017).

A holistic thermodynamic model covering the entire plant—not just the drying section—can reveal even greater efficiency gains. Investment in retrofitting heat recovery systems typically pays off within one year, even for older machines (Sivill & Ahtila, 2009).

However, the commercialization of heat recovery technologies through patents often hinders customized solutions. Without site-specific designs, many manufacturers lack the means to quantify energy savings (Treppe et al., 2012).

8. Discussion and Outlook

This chapter critically examines the current state of sustainability and energy efficiency initiatives in the nonwoven and paper industries, based on the findings of this literature review. The review's systematic approach and broad coverage contribute to a structured understanding of existing efforts. However, this work also acknowledges its methodological limitations, including its primary focus on German and European contexts and reliance on published literature. The analysis further highlights contradictions within current practices and the existing body of knowledge. The subsequent sections will elaborate on these identified gaps and present an outlook for future research and necessary developments (see Figure 18).

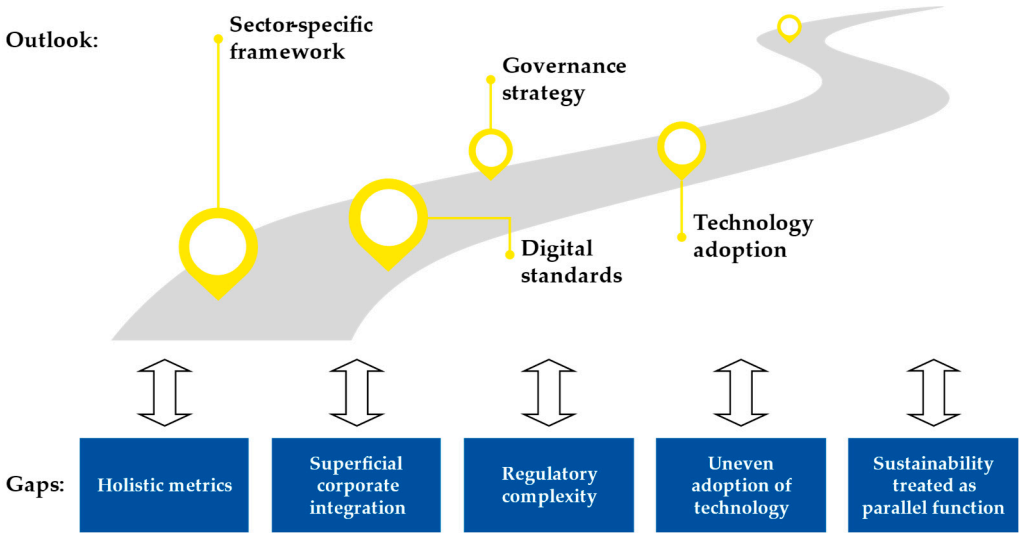

Figure 18. Key Barriers and identified strategies for advancing sustainability in fibre-based process sectors.

8.1. Gaps

Despite the breadth of initiatives, frameworks, and strategies addressing sustainability within the nonwoven and paper industries, several critical gaps persist in both theory and practice. First, there remains a lack of integration across the three core sustainability dimensions—ecological, economic, and social. While environmental metrics, particularly energy consumption and CO_2 emissions, are well developed and frequently applied (e.g., via ISO 50001, ISO 14067, LCA), corresponding indicators for the social and economic dimensions are underrepresented. Existing sustainability assessment models, such as OSEE or KPIs for ESG 3.0, provide valuable starting points, but holistic and industry-specific operationalization is still lacking. Moreover, the complexity and sector-specific nature of sustainability in the nonwoven industry, characterized by diverse applications and raw material sources, further complicate comparative assessments and standard-setting.

Second, strategic sustainability integration at the corporate level is often superficial. Empirical evidence shows that many companies focus on externally visible actions—such as product labelling or marketing—while neglecting deeper systemic transformation. Sustainability departments frequently lack the organizational authority and cross-functional integration required to drive lasting change. There is also insufficient strategic alignment between sustainability efforts and core business models, particularly in SMEs, where resources and expertise are often limited.

Third, regulatory fragmentation and bureaucratic complexity hinder effective implementation. Although the European Commission has introduced a comprehensive regulatory framework—including the CSRD, ESPR, and the Supply Chain Due Diligence Directive—practical implementation remains a challenge. Varying interpretations across member states, high documentation burdens, and unclear requirements contribute to compliance difficulties. This is particularly true for mid-sized firms and for sectors like hygiene and medical textiles, where sustainability progress is constrained by regulatory and performance requirements.

Fourth, while technological solutions for improving energy and material efficiency exist—such as smart metering, heat recovery, and high-efficiency machinery—their adoption is uneven. Barriers include high upfront costs, lack of site-specific implementation guidelines, and limited access to digital infrastructure. Moreover, circular economy models, although conceptually integrated into EU strategies, face practical obstacles such as low

recyclability of composite materials, inadequate material separation, and limited market uptake of secondary raw materials.

Finally, most current initiatives, including the SDGs, ISO standards, and corporate reporting systems, still treat sustainability as a parallel or complementary function rather than an embedded component of daily operations and strategic decision-making. There is a need for a truly integrated sustainability management system that addresses environmental, economic, and social dimensions simultaneously and adaptively across global value chains.

8.2. Outlook

To close the identified gaps, future research and policy should move towards developing integrated, sector-specific sustainability frameworks that address the full complexity of industrial ecosystems like nonwovens and paper. This includes creating harmonized indicators that capture the interplay between environmental impact, economic viability, and social responsibility. Tools such as hybrid LCA-S-LCA (social LCA) approaches, enriched with dynamic system modelling, could offer more robust decision-support frameworks for businesses and policymakers alike.

Second, embedding sustainability into the strategic core of businesses requires a shift in governance structures. Future studies should explore models for enhancing the internal influence of sustainability departments, fostering cross-departmental collaboration, and aligning performance incentives with sustainability outcomes. This includes extending current reporting frameworks such as the CSRD with qualitative and context-specific benchmarks that go beyond compliance toward transformation.

To reduce bureaucratic burdens, regulatory frameworks should be streamlined through digitalization. The establishment of a standardized European sustainability data infrastructure—based on interoperable, open, and machine-readable formats as mandated by the ESPR—can significantly improve administrative efficiency, particularly for SMEs. Furthermore, digital product passports and common reporting templates will facilitate traceability, comparability, and auditing across global supply chains.

On the technological side, demonstrators and publicly funded pilot projects should be promoted to accelerate the uptake of best available technologies, including heat recovery systems, renewable energy integration, and AI-supported energy management platforms. Such projects must prioritize modularity and adaptability to enable implementation across heterogeneous production settings. Financial incentives—such as green financing instruments and tax reliefs—should support investments in both infrastructure and workforce upskilling.

Circularity must be advanced through innovation in material science, such as the development of mono-material solutions and scalable bio-based inputs. Research into scalable recycling technologies tailored to nonwoven-specific challenges (e.g., adhesive separation, fibre heterogeneity) is also necessary. Multi-stakeholder collaboration across value chains, supported by shared data platforms and trust-enabling governance structures, will be essential for these advances.

Finally, global cooperation and standard harmonization are vital. Sustainability in the fibre-based sector must transcend national boundaries, addressing not only compliance but also competitiveness, innovation, and resilience. Future policy and research should foster international alignment of sustainability standards, facilitate technology transfer to emerging markets, and promote responsible global sourcing—thereby embedding sustainability into the fabric of industrial transformation worldwide.

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