DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DETERMINATION OF ENVIRONMENTAL IMPACTS OF GARMENT PRODUCTS AND INVESTIGATING CLEANER PRODUCTION ALTERNATIVES ON THE PERSPECTIVE OF RENEWABLE ENERGY, GREEN CHEMICALS AND DIGITALIZATION APPLICATIONS

by
Sema BAHAR ERDEM

February, 2026
İZMİR

DETERMINATION OF ENVIRONMENTAL IMPACTS OF GARMENT PRODUCTS AND INVESTIGATING CLEANER PRODUCTION ALTERNATIVES ON THE PERSPECTIVE OF RENEWABLE ENERGY, GREEN CHEMICALS AND DIGITALIZATION APPLICATIONS

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by
Sema BAHAR ERDEM

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İZMİR

Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DETERMINATION OF ENVIRONMENTAL IMPACTS OF GARMENT PRODUCTS AND INVESTIGATING CLEANER PRODUCTION ALTERNATIVES ON THE PERSPECTIVE OF RENEWABLE ENERGY, GREEN CHEMICALS AND DIGITALIZATION APPLICATIONS"** completed by **SEMA BAHAR ERDEM** under supervision of **PROF.DR. NURDAN BUYUKKAMACI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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DETERMINATION OF ENVIRONMENTAL IMPACTS OF GARMENT PRODUCTS AND INVESTIGATING CLEANER PRODUCTION ALTERNATIVES ON THE PERSPECTIVE OF RENEWABLE ENERGY, GREEN CHEMICALS AND DIGITALIZATION APPLICATIONS

ABSTRACT

The textile and garment industry is among the industrial sectors associated with considerable environmental impacts due to its intensive use of water, energy, and chemicals. In particular, wet processing and product development stages are critical phases where resource consumption and emissions are concentrated. Consequently, the identification of sustainable production approaches and effective strategies for reducing environmental impacts is of key importance for the sector.

This thesis aims to assess the environmental impacts of garment production processes using the life cycle assessment (LCA) methodology and to comparatively evaluate the environmental performance of selected cleaner production scenarios. These scenarios include renewable energy integration, the use of green chemicals, digitalization-based applications, and alternative washing processes. The system boundaries were defined to cover the production stage, enabling a consistent and holistic comparison of the evaluated scenarios.

The LCA was conducted in accordance with ISO 14040 and ISO 14044 standards. Primary data were collected from pilot-scale textile and garment production facilities, while secondary data were obtained from the literature and life cycle inventory databases. Cleaner production alternatives, including renewable energy use, ionic liquid–based dyeing, digital sampling applications, and ozone washing, were compared with conventional production practices.

The results demonstrate that renewable energy integration and digitalization applications significantly reduce greenhouse gas emissions and energy consumption. Ionic liquid–based processes decrease water and chemical use, while ozone washing shows potential for environmental improvement under suitable energy conditions. Overall,

this thesis provides a scientific basis to support sustainable production strategies in the textile and garment industry.

Keywords: Life cycle assessment, textile and garment industry, cleaner production, renewable energy, ionic liquid, digitalization

HAZIR GİYİM ÜRÜNLERİNİN ÇEVRESEL ETKİLERİNİN BELİRLENMESİ VE TEMİZ ÜRETİM ALTERNATİFLERİNİN YENİLENEBİLİR ENERJİ, YEŞİL KİMYASALLAR VE DİJİTALLEŞME UYGULAMALARI PERSPEKTİFİNDE ARAŞTIRILMASI

ÖZ

Tekstil ve hazır giyim sektörü, yoğun su, enerji ve kimyasal kullanımı nedeniyle önemli çevresel etkilere sahip endüstriyel sektörler arasında yer almaktadır. Özellikle yaş işlemler ve ürün geliştirme aşamaları, kaynak tüketimi ve emisyonların yoğunlaştığı kritik süreçlerdir. Bu nedenle, daha sürdürülebilir üretim yaklaşımlarının belirlenmesi ve çevresel etkilerin azaltılmasına yönelik stratejilerin değerlendirilmesi sektör açısından büyük önem taşımaktadır.

Bu tezin amacı, hazır giyim ürünlerinin üretim süreçlerinden kaynaklanan çevresel etkileri yaşam döngüsü analizi (YDA) yöntemi kullanarak değerlendirmek ve seçilen temiz üretim senaryolarının çevresel performansını karşılaştırmalı olarak incelemektir. Bu kapsamda, yenilenebilir enerji kullanımı, yeşil kimyasalların uygulanması, dijitalleşme temelli uygulamalar ve alternatif yıkama proseslerini içeren senaryolar ele alınmıştır. Sistem sınırları üretim aşamasını kapsayacak şekilde tanımlanmış ve farklı senaryolar bütüncül bir bakış açısıyla değerlendirilmiştir.

YDA çalışmaları ISO 14040 ve ISO 14044 standartlarına uygun olarak yürütülmüştür. Birincil veriler pilot ölçekli tekstil ve hazır giyim üretim tesislerinden elde edilirken, ikincil veriler literatürden ve yaşam döngüsü veri tabanlarından temin edilmiştir. Yenilenebilir enerji entegrasyonu, iyonik sıvı bazlı boyama, dijital numune hazırlama uygulamaları ve ozon yıkama prosesleri, konvansiyonel üretim yöntemleri ile karşılaştırılmıştır.

Elde edilen sonuçlar, yenilenebilir enerji kullanımı ve dijitalleşme uygulamalarının özellikle sera gazı emisyonları ve enerji tüketimi üzerinde önemli azalmalar sağladığını göstermektedir. İyonik sıvı bazlı prosesler su ve kimyasal tüketimini azaltırken,

ozon yıkama uygulamaları uygun enerji koşulları altında çevresel iyileştirme potansiyeli sunmaktadır. Genel olarak bu tez, tekstil ve hazır giyim sektöründe sürdürülebilir üretim stratejilerinin geliştirilmesine yönelik bilimsel bir temel sunmaktadır.

Anahtar kelimeler: Yaşam döngüsü değerlendirmesi, tekstil ve konfeksiyon sektörü, temiz üretim, yenilenebilir enerji, iyonik sıvı, dijitalleşme

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ABBREVIATIONS

[Bmim]Br	: 1-butyl-3-methylimidazolium bromide
[Bmim]Cl	: 1-butyl-3-methylimidazolium chloride
ADP	: Abiotic Depletion Potential
AP	: Acidification Potential
ATPE	: Aqueous Two-Phase Extraction
CML	: Centre of Environmental Science of Leiden University
CP	: Cleaner Production
EP	: Eutrophication Potential
FAETP	: Freshwater Aquatic Ecotoxicity Potential
FTIR	: Fourier Transform Infrared Spectroscopy
GWP	: Global Warming Potential
HT	: High Temperature
HTP	: Human Toxicity Potential
IL	: Ionic Liquid
LCA	: Life Cycle Assessment
LCI	: Life Cycle Inventory
LCIA	: Life Cycle Impact Assessment
MAETP	: Marine Aquatic Ecotoxicity Potential
ODP	: Ozone Depletion Potential
PET	: Polyethylene Terephthalate
POCP	: Photochemical Ozone Creation Potential
PS	: Physical Sample
TETP	: Terrestrial Ecotoxicity Potential
VS	: Virtual Sample

CHAPTER ONE
INTRODUCTION

1.1 Introduction

The textile and garment industry are one of the largest and most resource-intensive sectors worldwide, playing a significant role in economic development while simultaneously contributing to major environmental challenges. The production and consumption of garment products are associated with high levels of water consumption, energy demand, and chemical use, as well as substantial greenhouse gas (GHG) emissions and solid waste generation throughout their life cycles. Conventional textile finishing and processing techniques often rely on fossil-based energy sources and hazardous chemicals, leading to adverse impacts on ecosystems and human health. As worldwide environmental challenges gain urgency regarding climate change, resource scarcity, and environmental degradation, the sustainability of garment production has become an urgent research priority.

The textile and garment industry are estimated to account for approximately 2–4% of global greenhouse gas emissions, with its environmental footprint being further intensified by fast fashion business models that promote high production volumes, shortened product lifetimes, and accelerated textile waste generation (Niinimäki et al., 2020). According to the United Nations Environment Programme, the current linear "take–make–dispose" model dominating textile production is incompatible with global climate targets and resource availability, underscoring the need for systemic transformation rather than incremental efficiency improvements alone. Consequently, sustainability challenges in the garment industry must be addressed through integrated strategies that consider production technologies, energy systems, material choices, and consumption dynamics within a life cycle perspective.

In parallel with global environmental concerns, regulatory frameworks have increasingly directed the textile and garment industry toward more sustainable production practices. The European Green Deal (EGD), which aims to achieve a climate-neutral economy by 2050, identifies the textile sector as a priority industry requiring

urgent transformation and alignment with circular economy principles. These emerging obligations affect not only EU member states but also exporting countries such as Türkiye, turning compliance with sustainability-oriented regulations from a voluntary effort into a compulsory transition. The combined effect of these regulatory pressures and the growing awareness of the sector's environmental footprint has further highlighted the need for cleaner production approaches that can minimize resource use, reduce emissions, and support sustainable manufacturing pathways.

Recent years have witnessed growing attention to cleaner production strategies in the garment industry, aiming to minimize environmental impacts while maintaining economic viability and product quality. Among these strategies, renewable energy integration, the utilization of green chemicals, and digitalization-driven innovations are recognized as promising approaches. Renewable energy applications, such as solar, wind, and biomass, can reduce dependence on fossil fuels and significantly lower carbon emissions. Green chemicals, including bio-based and non-toxic alternatives, offer opportunities to substitute conventional hazardous substances in textile processing, reducing risks to both workers and consumers. Moreover, digitalization tools, such as smart manufacturing systems, artificial intelligence (AI), and digital product passports, have the potential to optimize resource efficiency, improve traceability, and enable circular economy practices. Recently, ozone-based washing processes have also been introduced as an alternative cleaner production method, particularly due to their potential to reduce chemical consumption during garment washing and finishing operations.

Despite the availability of these emerging alternatives, their environmental performance in the context of garment production requires an approach enabling an integrated analysis of impacts. Life cycle assessment (LCA) has become a widely adopted methodology for quantifying the environmental impacts of textile products and comparing alternative production techniques. By integrating LCA with cleaner production strategies, it is possible to identify critical hotspots, evaluate the benefits of renewable energy, green chemistry, digitalization, and ozone washing and propose practical solutions for sustainable garment manufacturing.

1.2 Purpose & Scope

The primary aim of this thesis is to determine the environmental impacts of garment products and to investigate cleaner production alternatives with a focus on renewable energy applications, green chemical use, digitalization, and ozone washing practices. Specifically, the study seeks to:

1. **Assess the environmental impacts** of conventional garment production processes across their life cycle stages using LCA.
2. **Identify environmental hotspots** within the garment production chain where significant improvements can be achieved.
3. **Evaluate the potential of renewable energy integration** in reducing carbon emissions and energy-related impacts in garment production.
4. **Investigate the application of green chemicals** as sustainable alternatives to conventional chemicals in textile processing.
5. **Explore the role of digitalization technologies** in enhancing process efficiency, resource optimization, and traceability in garment manufacturing.
6. **Evaluate the environmental performance of ozone-based washing processes** as an alternative to conventional washing methods.
7. **Provide recommendations for cleaner production strategies** that can contribute to a more sustainable garment industry.

The scope of the study covers garment production processes from raw material processing to the final product stage, focusing on both environmental performance and the feasibility of implementing cleaner production alternatives. By combining environmental assessment with technological innovation perspectives, this research aims to support the transition of the textile and garment industry towards sustainability, contributing to global climate and resource efficiency goals.

CHAPTER TWO
LITERATURE REVIEW

2.1 Environmental Impacts of Garment Production

2.1.1 Global Overview of the Garment Industry

The garment industry is one of the most significant consumer goods sectors, characterized by a highly complex global manufacturing structure (Jia et al., 2020). It is predominantly a labor-intensive, low-skilled assembly industry (Hamia et al., 2019). By 2030, the global textile market is expected to expand to a retail value on the order of USD 3 trillion, corresponding to an annual growth rate of approximately 5.8% (Leal Filho et al., 2024). Turkey holds approximately a 3.7% share in global textile trade (Alkaya and Demirer, 2014), exporting around 11.7 billion US dollars' worth of textiles, according to the World Trade Statistical Review 2020 by the World Trade Organization (WTO). Turkey occupies a significant position in the global textile industry, ranking as the fifth-largest exporter worldwide and serving as the second-largest textile supplier to the European market, following China. Furthermore, Turkey hosts some of Europe's largest textile production facilities across various sub-sectors (Kır et al., 2024).

The textile and clothing (T&C) sector comprise a sequence of interrelated and technically diverse manufacturing processes (Moazzem et al., 2021). The inherent complexity of the sector poses challenges for establishing a standardized classification system for its activities (EC, 2001). A simplified representation of the key stages within the T&C supply chain is provided in Figure 2.1.

Textile materials are conventionally divided into woven and knitted structures; however, considering the characteristics of the analysed garment processes in this thesis, the subsequent discussion is centred on knitted textiles.

As illustrated, the supply chain initiates with fiber production, which involves either the agricultural cultivation of natural fibers (e.g., cotton) or the industrial synthesis of man-made fibers derived from petrochemical sources (e.g., polyester). These fibers undergo spinning operations in yarn manufacturing units to produce yarns, which are subsequently converted into fabrics via weaving, knitting, or nonwoven technologies. The resulting fabrics are then transferred to garment manufacturing facilities, where they are assembled through cutting and stitching into final products, including apparel, fashion accessories, and home textiles (Agrawal et al., 2021)



Figure 2.1 Process flow diagram of the textile industry (Agrawal et al., 2021)

At its core, the garment industry transforms raw fibers into finished clothing products through a series of interlinked production stages. These stages can be broadly categorized as:

Fiber Production: Fiber production constitutes the initial stage of the textile manufacturing chain. Fiber materials are generally classified into two main categories: natural and man-made fibers (Bullon et al., 2017). Natural fibers originate from biological or mineral sources, including cotton, wool, sisal, and silk, while man-made fibers primarily comprise synthetics such as polyester, nylon, and acrylic (Chen et al., 2021).

In terms of fiber composition, global textile production is characterized by a strong predominance of synthetic fibers (≈60%), including polyester, acrylic, nylon (polyamide), and polypropylene. Cotton accounts for roughly one-third of total output, whereas other cellulosic fibers, wool, and flax (linen) together represent less than 10% of overall production (Koszewska, 2018).

Yarn production: Yarn spinning follows fiber production and involves steps such as opening, carding, combing, drawing, roving, spinning, and winding (Luján-Ornelas et al., 2020). The process aligns and twists fibers to form yarn. By varying fiber types and spinning methods, yarns with different properties can be produced. Regular yarns with uniform profiles can be twisted together to create multi-ply yarns (Wilson, 2001)

Fabric production: Yarns are woven, knitted, or non-woven into textile fabrics. The choice of technique influences the final properties of the fabric, including stretchability, texture, and strength.

Wet Processing (Pre-treatment, Dyeing, and Finishing): Textile wet processing comprises pre-treatment, dyeing, and finishing (Moazzem et al., 2021). Pre-treatment steps such as washing, scouring, and bleaching which remove impurities and prepare the fabric for uniform dyeing (Luján-Ornelas et al., 2020). Bleaching is especially important for white or light-colored textiles. Dyeing usually occurs in aqueous media, allowing dyes to bond effectively with fibers. Finishing enhances textile appearance or performance through mechanical (e.g., calendering) or chemical methods that impart properties like softness, anti-static behavior, or flame resistance (Broadbent, 2001).

Garment Manufacturing: Garment manufacturing represents the final stage of the textile and clothing value chain, in which fabric is cut, sewn, and assembled into finished garments. This phase is highly labor-intensive and frequently outsourced to countries with lower labor costs. In addition to stitching operations, this stage also includes quality control, trimming, labeling, and packaging activities before the products are ready for distribution.

Distribution and Retail: Finished garments are packaged, shipped, and distributed to global markets. Increasingly, digital retail channels and global logistics have shortened delivery cycles, especially in fast fashion systems.

Use Phase and End-of-Life: The use phase encompasses retail activities, consumer transportation related to garment purchasing, and clothing maintenance practices during use. The end-of-life (EOL) stage refers to the management of garments once they are no longer used, following their initial or repeated use, with reuse already accounted for in the total number of wears over the garment's lifetime (Wiedemann et al., 2020). Discarded textiles may follow various EOL pathways, including reuse through charitable donation, export for secondary use in other regions, recycling, remanufacturing, or disposal. Among these options, landfilling remains the predominant practice, with the majority of garments ultimately disposed of in this manner. On a global scale, approximately 87% of post-consumer textile waste is directed to landfill or incineration (Moazzem et al., 2021).

2.1.2 Pollution and Resource Use in the Textile Industry

The textile sector relies on a wide range of raw materials—from natural fibers such as cotton to petroleum-based synthetic fibers—and requires intensive use of energy, water, and chemicals throughout its production processes (Niinimäki and Hassi, 2011). In addition to extensive resource consumption, the industry contributes substantially to environmental degradation through greenhouse gas emissions, wastewater generation, and solid waste production (Mikucioniene et al., 2024; Radhakrishnan, 2022). These impacts occur across both upstream and downstream stages of the supply chain; however, this section focuses exclusively on the environmental burdens associated with the production stage.

Cotton cultivation is the largest source of water use in the textile life cycle because it requires intensive irrigation (Chapagain et al., 2006). For this reason, cotton cultivation appears as the dominant contributor to total water consumption, as shown in Figure 2.2. At the factory level, however, water use is mainly concentrated in wet processing steps such as bleaching, dyeing, printing, and finishing (Khan and Islam, 2015). Among these processes, dyeing and finishing are the most water-intensive operations and account for nearly 20% of global industrial water pollution (Khatri et al., 2015; Lara et al., 2022; Gonzalez et al., 2023). Traditional dyeing processes require

approximately 100–180 L of water per kilogram of fiber depending on the fiber type, dye class, and machinery used. As a result, overall water demand is exceptionally high: a typical dyeing and finishing facility may consume around 150 m³ of water per tonne of fabric, and factories processing 8,000 kg of fabric per day can use up to 1.6 million liters of water (Hasanbeigi and Price, 2015). In contrast, mechanical operations such as spinning, weaving, and knitting require minimal water input (Alam and Hossain, 2018). Collectively, the textile industry consumes around 40 billion cubic meters of freshwater annually to produce 60 billion kilograms of fabric, highlighting its substantial environmental burden (Muthu and Gardetti, 2020).

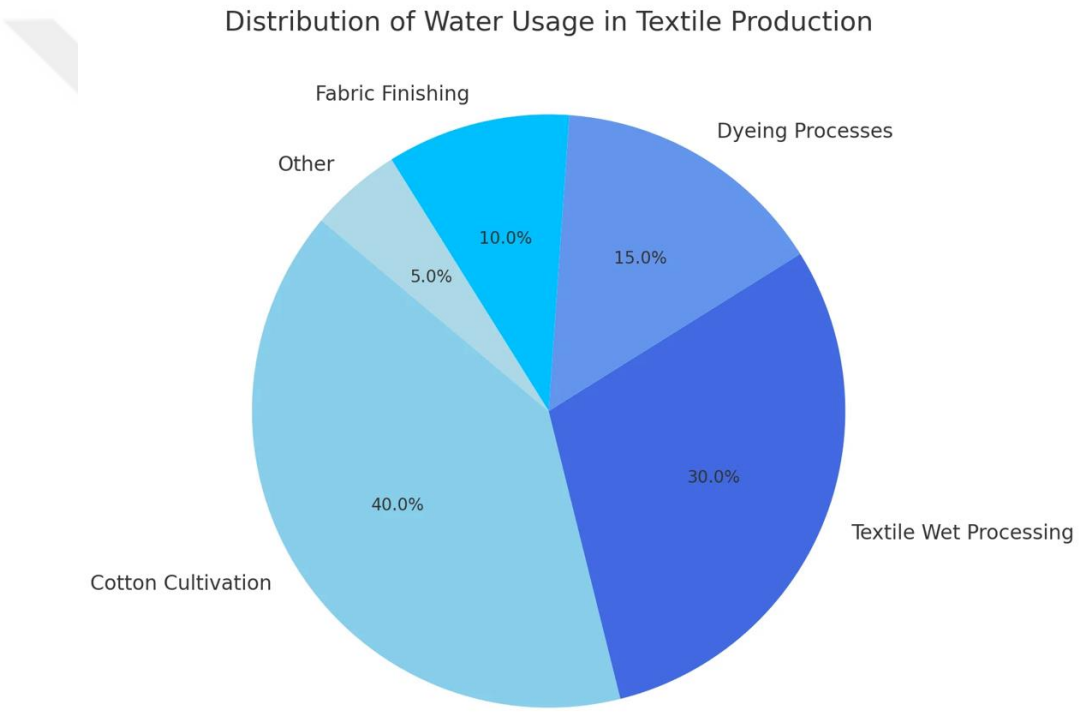


Figure 2.2 Distribution of water use across textile production stages (Source: Best Colorful Socks, n.d.)

The intensive water uses in wet processing results in large volumes of wastewater discharge. Effluents generated from dyeing, printing, and finishing operations are typically hot and highly colored, with elevated concentrations of organic matter, dissolved solids, and salts (Madhav et al., 2018; Zhang et al., 2023). In many textile-producing regions, more than 80% of industrial wastewater originates from these wet processing

activities (Hussain and Wahab, 2018). Such wastewater streams pose significant challenges for treatment and are major contributors to aquatic pollution.

The textile industry is recognized as one of the largest industrial users of hazardous chemicals (Gonçalves, 2021). The cumulative use of chemicals in textile processing is extensive; it is estimated that over 2,000 different chemical compounds are employed across the industry, ranging from dyes and mordants to transfer agents and finishing auxiliaries (Jain, 2017). Dyeing processes, in particular, involve a wide array of potentially harmful substances, including zinc, formaldehyde, and hexavalent chromium (Cr VI)—all of which pose varying levels of ecological and human health risk when discharged into aquatic environments (Belal and Mehta, 2020).

The textile industry is a major energy consumer, utilizing both electrical and thermal energy across its various processes. Electricity is primarily used to power machinery, lighting, climate control, and motor systems in textile production. Thermal energy, typically derived from fossil fuels such as coal, oil, LPG, and natural gas, is mainly used to generate steam for wet processes including dyeing, washing, bleaching, and finishing (Farhana et al., 2022). Among all stages, wet processing is the most energy- and water-intensive, with steam often required at temperatures ranging from 60°C to 200°C (Hasan and Leones, 2018). Energy use also varies by sub-sector: spinning and knitting primarily rely on electricity, while weaving and garment production incorporate thermal energy, particularly for sizing and steam ironing (Farhana et al., 2022). In addition, the production of synthetic fibers such as polyester, viscose, and nylon is significantly more carbon-intensive than that of natural fibers due to their petrochemical origins (Munasinghe et al., 2016). As a result, the fashion industry is estimated to account for approximately 10% of global carbon emissions, positioning it among the most polluting industries after oil (Muthukumarana et al., 2018).

Solid waste is a significant environmental issue in the textile industry, emerging at nearly every stage from production to consumption. Globally, textile waste is estimated to account for approximately 1.5% of total solid waste generation (Sanjrani et al., 2025). Within the European Union, around 5.8 million tonnes of textile waste are

generated annually; however, only 1.5 million tonnes (25%) are recycled, while the remaining 4.3 million tonnes are sent to landfills or municipal incineration facilities (Yacout and Hassouna, 2016). Textile waste is generally classified into three categories: production waste, pre-consumer waste, and post-consumer waste. Among these, fabric offcuts and roll ends constitute a substantial portion of manufacturing waste (Yalçın-Enis et al., 2019). Cutting waste alone may range between 6% and 25%, depending on the complexity of the pattern, and is often recycled into lower-grade textile products (Khan and Islam, 2015). In addition, significant amounts of solid waste are generated during operational stages such as design, stock handling, cutting, sewing, finishing, and packaging (Nyika and Dinka, 2022). Through sustainable waste management, including reuse, recycling, and the application of circular economy practices, the environmental burden of textile waste can be significantly reduced, and the lifecycle of materials can be extended (Nyika and Dinka, 2022). Packaging materials, including plastic wrapping, polybags, paper labels, and cardboard, account for approximately 8–10% of total solid waste generated in textile production (Pranta et al., 2025).

In addition to macro-scale environmental impacts such as water use, chemical consumption, and energy demand, textiles also contribute significantly to micro-scale pollution. The sector is one of the largest sources of microfibers released into the environment. Textiles are considered one of the largest sources of microfibers in the environment. While synthetic fibers such as polyester, nylon, and polypropylene are major contributors, studies indicate that natural fibers like cotton and wool also play a substantial role in microfiber pollution in freshwater ecosystems and atmospheric deposition (Liu et al., 2021).

If current apparel consumption patterns remain unchanged, global consumption is projected to surge from 62 million tons in 2015 to 102 million tons in 2030, representing a 63% increase. This rise is expected to significantly amplify the environmental footprint of the textile industry, with water and energy consumption growing by 50% and 63%, respectively, and waste generation and chemical use increasing by 62% (Moazzem et al., 2021).

Garment production has lower environmental intensity than fiber production and wet processing, but it still contributes noticeably to the overall footprint of the textile industry. Cutting operations generate a considerable amount of fabric waste. Sewing and ironing require continuous electricity and thermal energy. Garment washing can also involve significant water and chemical use, depending on the process applied. In addition, plastic-based packaging materials increase solid waste at this stage (Figure 2.3). These impacts show that improvements in garment production can meaningfully reduce the environmental burden of textile manufacturing.

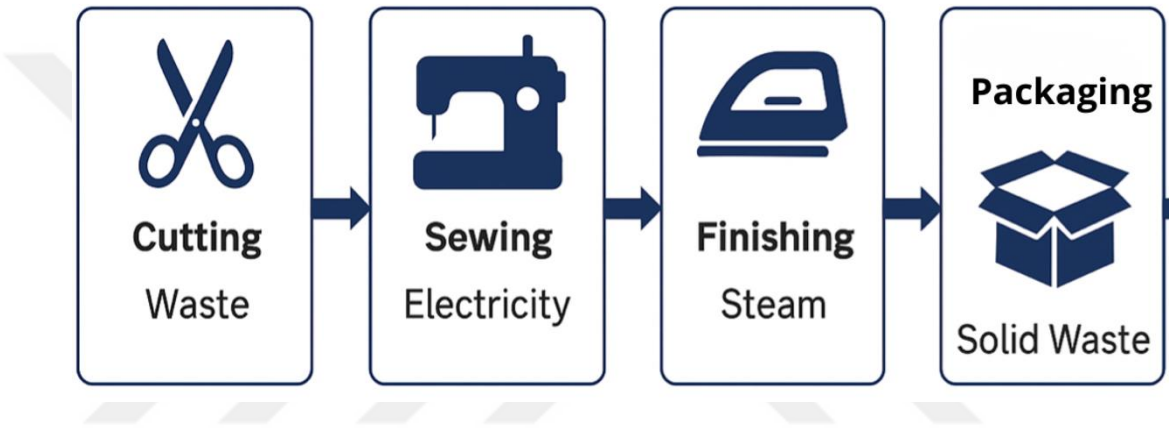


Figure 2.3 Environmental hotspots across garment production stages

These environmental burdens accumulate along the entire value chain, including garment manufacturing. Therefore, adopting cleaner production practices across both textile processing and garment manufacturing is crucial for reducing the sector's overall environmental footprint.

2.2 Life Cycle Assessment (LCA) in the Textile Industry

LCA provides a structured framework for quantifying the environmental impacts of a product throughout its entire life cycle, encompassing stages from raw material acquisition to final disposal (ISO, 2006; Guinée et al., 2011). Within the textile sector, LCA is widely applied to pinpoint impact-intensive stages, support informed material

selection, and assess the environmental performance of cleaner and more sustainable production technologies.

2.2.1 Principles and Methodologies of LCA (ISO 14040/44)

Life Cycle Assessment (LCA) emerged in response to rising environmental awareness during the late 1960s and early 1970s, when concerns over pollution, energy consumption, and waste prompted the first efforts to evaluate products' environmental performance. Although early applications were limited in scope, they laid the groundwork for today's standardized and comprehensive LCA frameworks (Nikolic et al., 2019).

By adopting a life-cycle perspective, LCA captures environmental impacts generated at each stage of a product system, from upstream resource extraction to downstream end-of-life processes, as illustrated in Figure 2.4 (Ranasinghe and Jayasooriya, 2021). It is widely regarded as one of the most effective tools for identifying resource consumption, emissions, and ecological burdens (Nikolic et al., 2019). In addition to measuring waste and emissions, LCA helps assess broader environmental metrics, such as water and energy use, carbon emissions, and the effectiveness of environmentally friendly technologies (Roy Choudhury, 2014). The process is guided by the international standards ISO 14040:2006 and 14044:2006 which provide a consistent and comparable structure for conducting assessments (Van Der Giesen et al., 2020; De Benedetto and Klemeš, 2009).

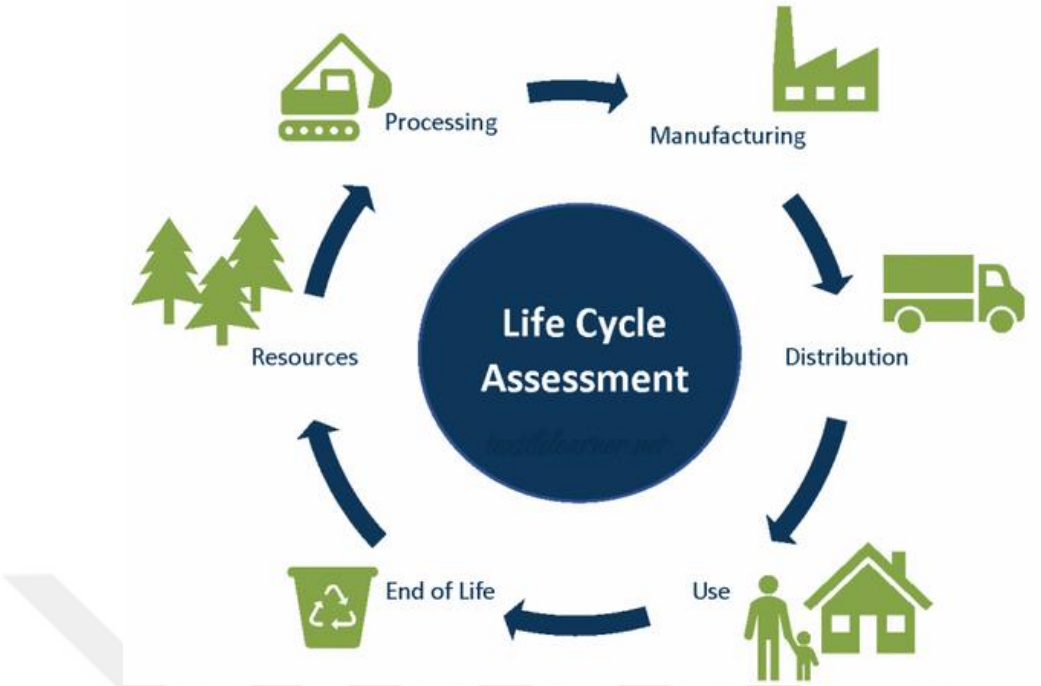


Figure 2.4 Key stages of the Life Cycle Assessment (LCA) system for textile products (Source: Textile Learner, n.d.)

According to ISO guidelines, an LCA study consists of four interrelated phases: (1) Goal and Scope Definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation (ISO Standards, 2006). These phases are not strictly linear but form an iterative framework, where findings from later stages may lead to revisions in earlier ones. As illustrated in Figure 2.5, interpretation plays a central role, continuously interacting with all other stages to ensure consistency and refinement throughout the assessment process.

In the first phase, practitioners define the purpose of the study, identify the functional unit, and determine the system boundaries. This is followed by the inventory phase, where all relevant data on resource use (such as energy, water, and materials) and environmental outputs (such as emissions and waste) are gathered for each stage of the product's life cycle from cradle to grave (Rebitzer et al., 2004). The LCI phase compiles and quantifies these material and energy flows in a systematic way (Ekvall and Finnveden, 2001). The third phase, LCIA, links this data to specific environmental impacts using predefined categories and indicators, mapping these relationships within

a cause-effect chain (Jolliet et al., 2003). In this stage, environmental impact categories such as eutrophication, acidification, ozone depletion, resource depletion, global warming, toxicity, and effects on human health and ecosystems are assessed. To evaluate these impact categories, various methodologies including EPD2007, EDIP 2003, CML 2001, EPS 2000, ReCiPe, Eco-indicator 99, Eco-indicator 95, CML 92, and EDIP/UMIP have been developed (Moazzem et al., 2021). Finally, the interpretation phase synthesizes the findings, identifies significant issues, and guides recommendations based on the outcomes.

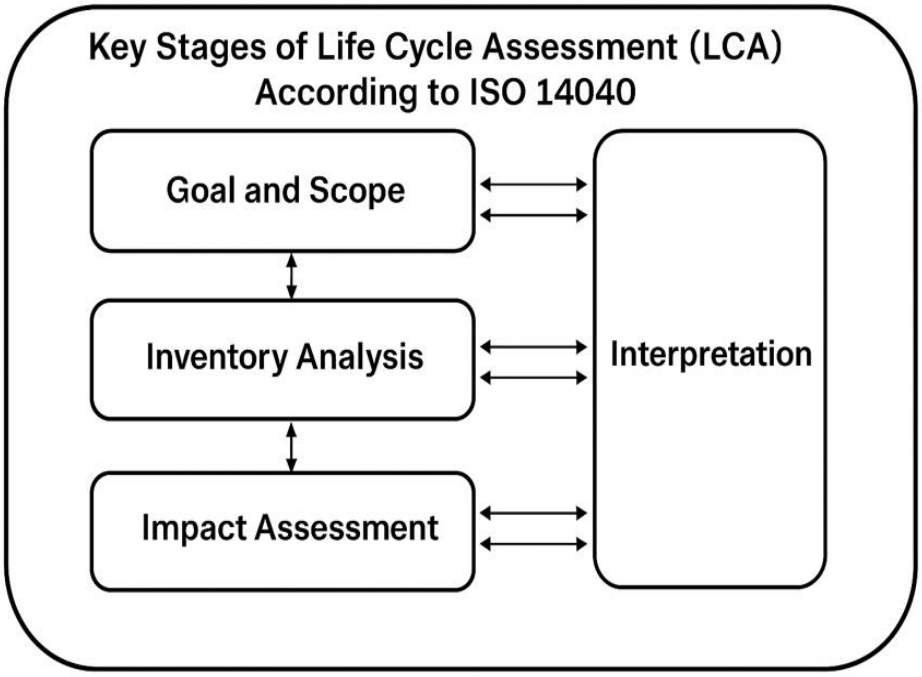


Figure 2.5 Framework of Life Cycle Assessment (LCA) According to ISO 14040 (ISO Standards, 2006).

In a sector marked by high levels of environmental pressure, such as textile manufacturing, LCA serves as a critical analytical tool. It enables the assessment of each stage, such as fiber production, yarn and fabric processing, dyeing, finishing, and end-of-life disposal, and identifies which stages contribute most significantly to environmental degradation (Aguiar et al., 2023; Nieminen et al., 2007). By pinpointing these

hotspots, LCA informs the development and implementation of cleaner, more sustainable technologies (Ranasinghe and Jayasooriya, 2021).

A range of software tools is now available to help model the life cycle impacts of products, processes, and services. Among these, certain platforms have gained considerable popularity and are widely utilized for LCA applications (Muthu, 2020). Tools like SimaPro, GaBi, OpenLCA, and Umberto streamline the modeling process by leveraging robust databases such as Ecoinvent and Agri-footprint, which supply essential emission factors and background process data for precise evaluations.

Overall, applying LCA in the textile industry enables a holistic understanding of environmental burdens and supports the transition to cleaner production, resource efficiency, and circular economy strategies.

2.2.2 Review of Previous LCA Studies on Garment Products

In LCA studies evaluating the environmental impacts of textile and apparel products, focusing solely on the manufacturing stages of a garment is not sufficient. The overall environmental burden of a garment is largely shaped by numerous upstream processes that occur long before the garment production stage. Therefore, the environmental impacts associated with earlier phases such as fiber cultivation or production, yarn formation, fabric manufacturing, and wet processing must also be included within the system boundaries. A significant portion of the literature adopts this broader approach. However, while some studies investigate specific garment types or fibers, others employ narrower system boundaries and examine only certain life cycle stages, such as dyeing or finishing (Moazzem et al., 2021). A comprehensive summary of selected LCA studies conducted in the textile sector, including functional units, system boundaries, impact categories, software tools, and references, is presented in Table 2.1.

Table 2.1 Overview of LCA studies in the textile industry

Reference	Product / Fiber	Functional Unit	System Boundary	Impact Categories	Software / DB	Hotspots:
Astudillo et al., 2014	Raw silk	1 kg raw silk	Cradle-to-gate	CED, GWP100, ecotoxicity, land occupation, freshwater eutrophication	SimaPro 8.0.2	Silkworm rearing and steam/heat use during processing.
Horn et al., 2023	Polyester T-shirt	One use of a T-shirt	Cradle-to-grave	GWP, water scarcity, eutrophication, acidification, resource depletion (EF 2.0)	Excel model + ecoinvent 3.3	Consumer use phase (washing, drying) and polyester production.
Shen et al., 2010	Viscose, Modal, Tencel staple fiber	1 tonne of staple fiber	Cradle-to-gate	GWP100, abiotic depletion, toxicity, acidification, eutrophication (CML 2)	N/A	Pulp production and energy use in chemical processing.
La Rosa et al., 2019	Cotton, kenaf, jute fiber	1 kg fiber	Cradle-to-gate	Water depletion, CED, acidification, eutrophication	SimaPro 8.0.5	Irrigation for cotton; retting for jute and kenaf.
Kazan et al., 2020	1000 shirts	1000 shirts	Cradle-to-gate	All CML 2001 impact categories	GaBi 8.0	Fabric production and dyeing; upstream energy demand significant.
Abu-Qdais et al., 2021	Multiple nanosilver textile products	1 product (various forms)	Cradle-to-grave	TRACI 2.1: GWP, ozone depletion, acidification, eutrophication, toxicity, fossil depletion	SimaPro 9.0	Silver nanoparticle synthesis and energy use in finishing processes.
Avadi et al., 2020	Seed cotton & baled cotton fiber	1 t or 1 ha cotton	Cradle-to-gate	ILCD 2011 Midpoint+	SimaPro 9.0	Fertilizer application and irrigation at farm level.
Baydar et al., 2015	Dyed cotton T-shirt	1000 items	Cradle-to-grave	GWP, acidification, aquatic & terrestrial eutrophication, photochemical ozone formation (EDIP 2003)	GaBi 5	Dyeing/finishing processes and electricity consumption.
Bech et al., 2019	100% merino wool T-shirt	1 T-shirt	Cradle-to-grave	Climate change (ReCiPe)	SimaPro 8.1.1	Sheep farming due to methane emissions and land use.

Table 2.1 Overview of LCA studies in the textile industry

Reference	Product / Fiber	Functional Unit	System Boundary	Impact Categories	Software / DB	Hotspots:
Bevilacqua et al., 2014	Dyed cotton yarn	1 kg yarn	Cradle-to-gate	Eco-indicator 99 + IPCC 2007	N/A	Dyeing stage and thermal energy consumption in yarn processing.
Bianco et al., 2022	100% recycled wool fiber	1 kg fiber	Cradle-to-gate	EF 3.0 (climate change, ozone depletion, particulate matter, eutrophication, eco-toxicity, land & water use, resource use)	SimaPro 9.2	Electricity use in recycling; significant reductions vs virgin wool.
Busi et al., 2016	Finished textile	1 kg textile	Gate-to-gate	CED, GWP100 (ReCiPe)	SimaPro 7.3.3	Thermal energy use in finishing processes.
Esteve-Turrillas & de la Guardia, 2017	Recovered coloured cotton yarn	1 kg yarn	Gate-to-gate	GWP, AP, EP, water use	GaBi	Electricity consumption during shredding and reprocessing.
Farrant et al., 2010	Various apparel items	100 garments (use phase)	Cradle-to-grave	EDIP: acidification, GWP, nutrient enrichment, ozone depletion, photochemical oxidants	GaBi	Consumer washing & drying; extending garment life reduces impacts.
Fidan et al., 2021	Finished denim fabric	1 meter fabric	Cradle-to-gate	GWP, AP, EP, water use, CED	SimaPro 8.4.1	Denim finishing (especially stone washing) and electricity demand.
González-García et al., 2010	Fiber for pulp processing	1 ton fiber	Cradle-to-gate	CML 2000: GWP, acidification, eutrophication, photochemical oxidation	SimaPro 7.0	Energy use in pulp production; forestry operations contribute to acidification.

Table 2.1 Overview of LCA studies in the textile industry (continue)

Reference	Product / Fiber	Functional Unit	System Boundary	Impact Categories	Software / DB	Hotspots:
Gonzalez et al., 2023	Various natural fibers	1 kg fiber	Cradle-to-gate	ReCiPe Midpoint (2016): fossil resource scarcity, GWP, land use, terrestrial ecotoxicity, water consumption	N/A	Vary by fiber: cotton dominated by water use; silk by energy; jute/flax by land occupation.
Hammar et al.,2024	Knitted hoodie (recycled carbamate +organic cotton)	1 garment+1 day of wear	Cradle-to-grave	GWP (IPPC), water scarcity (AWARE), land use (LANCA)	SimaPro 9.5	Yarn production, finishing, and use phase; recycle fiber reduce impacts.
L'Abbate et al., 2018	100% PET ticking	1 kg textile	Cradle-to-grave	GWP, toxicity, acidification, particulate matter, eutrophication, resource depletion	GaBi	PET resin production and thermal energy use in finishing.
Lenzo et al., 2018	60% wool, 40% cashmere garment	1 garment	Cradle-to-gate	ReCiPe Midpoint (H) v1.09	N/A	Livestock emissions (methane) and energy use in knitting/finishing.
Liu et al., 2020	Produced yarn	1000 kg yarn	Cradle-to-gate	GWP, fossil depletion, water depletion, human toxicity	GaBi	Electricity consumption in spinning; upstream fiber production shapes impacts.
Mahiat et al., 2023	100% cotton woven fabric	1 ton fabric	Gate-to-gate	ReCiPe 2016	SimaPro 9.1	Thermal energy in dyeing/finishing; electricity dominates CED.
Martin & Herlear, 2021	Wool sweater from waste wool	1 sweater	Cradle-to-gate	ILCD 1.0.8 midpoint	OpenLCA	Collection and shredding stages; clear benefits vs virgin wool systems.

Table 2.1 Overview of LCA studies in the textile industry (continue)

Reference	Product / Fiber	Functional Unit	System Boundary	Impact Categories	Software / DB	Hotspots:
Moazzem et al., 2018	Apparel from various fibers	1 kg apparel (use-phase focus)	Cradle-to-grave	CML baseline	OpenLCA	Consumer washing & drying; fiber type strongly affects total impacts.
Moazzem et al., 2021bApparel products	Apparel from cotton, polyester, viscose etc.	1 kg apparel (in use)	Cradle-to-grave	CML + ReCiPe (water depletion, land occupation)	OpenLCA	Use phase energy demand; polyester shows higher GWP, cotton higher water use.
Montaya Flores and Salhofer,2025	Cotton T-shirt	1 T-shirt	Cradle-to-grave	CML 2001, ReCiPe 2016, AWARE	GaBi	Cotton cultivation (irrigation, fertilizers) and drying; water scarcity dominated by irrigation
Morita et al., 2020	Trouser jeans	1 pair jeans	Cradle-to-gate	Climate change, primary energy demand	—	Cotton farming and fabric production; finishing processes increase energy burden.
Muthukumarana et al., 2018	100% cotton blouse	1 blouse	Gate-to-gate	ReCiPe Midpoint 1.11	SimaPro	Dyeing and drying operations; electricity demand prominent.
Parisi et al., 2015	Woollen fabric	1 kg fabric	Gate-to-gate	CML 2001	SimaPro 7.3.3	Steam and electricity use in finishing stages.
Periyasamy et al., 2017	Denim jeans	1 jeans	Cradle-to-gate	ReCiPe 2008 (toxicity, ecotoxicity, ozone depletion, land transformation, etc.)	—	Cotton cultivation and dyeing; chemical-intensive steps drive toxicity.
Sandin et al., 2013	Dry metric tonne staple fiber	1 tonne fiber	Cradle-to-gate	Eco-indicator 99	—	Upstream chemical production and energy use in fiber processing.

Table 2.1 Overview of LCA studies in the textile industry (continue)

Reference	**Product / Fiber**	**Functional Unit**	**System Boundary**	**Impact Categories**	**Software / DB**	**Hotspots:**
Sener Fidan et al., 2023	Jeans with 45.5 cycle lifetime	1 pair jeans	Cradle-to-grave	CML-IA: GWP, EP, AP, ecotoxicity	SimaPro 9.2.02	Cotton farming + consumer laundering; finishing processes add significant AP/EP
Terinte et al., 2014	Dyed & finished modal fabric	1 kg fabric	Cradle-to-gate	CML 2001	—	viscose–modal fiber production and thermal energy in wet processing.
Wiedemann et al., 2020	Fine Merino wool sweater	300 g sweater	Cradle-to-grave	IPCC GHG, fossil energy, WSI	SimaPro 9.0	sheep methane emissions and electricity for drying during use.
Yacout et al., 2016	Acrylic fiber	1 kg fiber	Cradle-to-gate	Eco-indicator 99	SimaPro 7.1	fossil-based raw materials and polymerisation energy.
Zhang et al.,2015	Cotton short-sleeve T-shirt	1 T-shirt	Cradle-to-grave	CML2001+USEtox	GaBi 6.0	Use-phase washing/drying; wet processing drives toxicity impacts.

As presented in Table 2.1, these studies provide valuable insight into the methodological diversity and key environmental hotspots associated with textile and apparel products.

For instance, Horn et al. (2023) assessed the environmental impacts of a polyester T-shirt over its full life cycle using a cradle-to-grave boundary and Excel-based modeling, focusing on indicators such as global warming, water scarcity, and eutrophication. In contrast, Kazan et al. (2020) modeled 1000 shirts within a cradle-to-gate framework using GaBi software, applying the CML 2001–January 2016 method, which enabled the identification of upstream production impacts. More recently, Hammar et al. (2024) conducted a cradle-to-grave LCA of a hoodie produced from chemically recycled cellulose carbamate fiber, integrating both conventional and circular value-chain processes and demonstrating the potential environmental benefits of fiber recycling technologies. In addition, Montoya Flores and Salhofer (2025) conducted a cradle-to-grave study on a cotton T-shirt produced in Peru and found that cotton cultivation and the use phase, especially drying, are the main contributors to environmental impacts.

Studies have also varied in their choice of functional units. While some analyses (e.g., Shen et al., 2010; La Rosa et al., 2019) focus on 1 kg of textile fiber or fabric, others (e.g., Bech et al., 2019; Farrant et al., 2010) consider individual garments or consumer usage scenarios. This variation significantly affects the interpretation of results, particularly when comparing products with different weights, fiber compositions, or use-phase behaviors.

A wide range of impact categories has been adopted. Global warming potential (GWP) remains the most commonly assessed indicator across all reviewed studies (e.g., Bevilacqua et al., 2014; Fidan et al., 2023), followed by acidification, eutrophication, and cumulative energy demand (CED). Some researchers (e.g., Bianco et al., 2022; Moazzem et al., 2021) have adopted broader frameworks such as Environmental Footprint 3.0 or ReCiPe Midpoint, which also include toxicity, resource depletion, and land use indicators.

Regarding software tools, SimaPro is the most frequently used (e.g., Abu-Qdais et al., 2021; Wiedemann et al., 2020), followed by GaBi and OpenLCA. Some studies (e.g., Horn et al., 2023) use Excel with secondary data sources, such as ecoinvent, to model simpler systems.

The reviewed literature consistently identifies key hotspot stages in garment product life cycles. These include fiber production (especially for synthetic or water-intensive fibers), dyeing and finishing processes, and the use phase (particularly consumer washing and drying). For example, Zhang et al. (2015) reported significant GWP and toxicity impacts during the use phase of a cotton T-shirt, while Fidan et al. (2021) emphasized the high energy demand associated with denim finishing processes.

The analysis of previous LCA studies on garment products reveals that, despite considerable differences in methodological choices such as functional units, system boundaries, and impact assessment methods certain stages of the life cycle are consistently identified as environmental hotspots. In particular, the production phase (including fiber manufacturing, dyeing, and finishing) and the consumer use phase (washing, drying, ironing) emerge as the most significant contributors to environmental burdens.

This variation in methodological granularity and underlying assumptions across studies poses challenges for direct comparison and benchmarking. Rather than attempting to align or compare results across fundamentally different studies, each LCA should be regarded as a context-specific tool to identify environmental hotspots within a given system. The primary focus should therefore shift toward using LCA findings to inform process improvements, guide cleaner production strategies, and support evidence-based decision-making aimed at reducing environmental impacts in the specific context of the study.

Building upon this understanding, the present thesis aims to conduct a comprehensive life cycle assessment of selected garment products to quantify their environmental impacts and, more importantly, to explore cleaner production alternatives. By integrating LCA findings with innovative solutions, this study aims to provide practical and

sustainable recommendations for textile manufacturing. These solutions include the use of renewable energy, green chemicals, digitalization, and ozone-based processes to reduce environmental burdens. The next section therefore focuses on the concept of cleaner production and its relevance to sustainability in the textile industry.

2.3 Cleaner Production Approaches in the Textile Industry

Cleaner Production (CP) is a dynamic environmental management approach aimed at preventing environmental impacts at their source, supported by the continuous development of new procedures and technologies (Giannetti et al., 2020). This approach is based on the more efficient use of energy and materials, as well as the substitution of environmentally and human health–hazardous inputs with safer alternatives (Hens et al., 2018). It also integrates environmentally friendly practices such as preventing pollution before it occurs, minimizing waste generation, recycling, and converting waste resources into new products (Gavrilescu, 2004). The United Nations Environment Programme (UNEP) defines cleaner production as *"the continuous application of an integrated environmental strategy to processes, products, and services to reduce risks to humans and the environment."* Such strategies make significant contributions to improving the technical, environmental, and economic performance of industrial enterprises (Ozturk et al., 2016).

The textile industry is highly dependent on natural resources such as raw materials, water, and energy for production, and it also poses adverse impacts on the environment and human health due to the intensive use of chemicals. Therefore, CP practices have been gaining increasing importance in the sector (Xu et al., 2024). In 2003, the European Commission published the *Best Available Techniques* (BAT) reference document for the textile industry, outlining a range of advanced methods aimed at improving environmental performance. BAT and other innovative technologies include enzymatic treatments, ultrasonic processes, advanced cotton fiber pretreatments to enhance dye uptake, plasma technology, and foam technology in finishing operations, which have been reported to achieve up to 65% water savings and 70% energy savings (Chen et al., 2017; Gönlügür, 2019). Furthermore, the reduction or substitution of hazardous

chemicals with environmentally friendly alternatives represents a key component of CP strategies (Malleval, 2022).

Various tools have been developed to identify cleaner production opportunities; each suited to different application areas. The choice of tool depends on the nature of the problem encountered in the facility and the scope of the intended work (Büyükkamacı et al., 2023). Among these tools, the most widely used is the Life Cycle Assessment (LCA) approach. The environmental "hotspots" identified through LCA provide critical guidance on which processes and at what scale CP measures should be implemented. In practice, the successful implementation of cleaner production strategies requires a systematic decision-making framework capable of evaluating environmental trade-offs across different processes and improvement options (Giannetti et al., 2020). Process-level efficiency gains or single-technology substitutions may lead to unintended burden shifting if upstream and downstream impacts are not simultaneously considered. Therefore, cleaner production is increasingly approached not only as a set of technological interventions, but also as an integrated assessment-driven strategy that prioritizes interventions based on their overall environmental performance. In this context, life cycle thinking plays a critical role by enabling the comparison of alternative cleaner production options on a consistent basis and by supporting the selection of improvement measures that deliver net environmental benefits across the entire production system (Giannetti et al., 2020; Guinée et al., 2011). In this thesis, based on the LCA results, four cleaner production strategies have been evaluated: renewable energy use, green chemical applications, digitalization, and ozone washing improvements.

2.3.1 Renewable Energy

The textile industry is characterized by high consumption of both electrical and thermal energy. Electricity is used for operating motors, climate control, and lighting, while thermal energy is required for processes such as bleaching, dyeing, and other finishing operations (Dehshiri and Firoozabadi, 2025). A large share of energy consumption occurs in yarn and fabric production (40–45%) and in wet processing units

(35–60%) (Farhana et al., 2022). Spinning and weaving stages rely entirely on electricity, whereas processes like sizing, dyeing, and drying require thermal energy to heat water or dry fabrics. It is reported that globally, approximately 1 trillion kWh of electricity is consumed annually to produce 60 billion kg of fabric. This high energy demand makes the sector responsible for about 10% of annual global greenhouse gas emissions, corresponding to 1.2 billion tons of CO_2 (Bibi et al., 2024; Okafor et al., 2021).

In the textile sector, most electricity and heat energy are generated from non-renewable fossil fuels such as oil, hydrocarbon gas liquids, natural gas, and coal (Kousar et al., 2022). The rapid depletion of fossil fuels and their role in increasing greenhouse gas emissions necessitate the adoption of alternative energy sources. Renewable energy sources, such as solar, wind, biomass, tidal, and hydropower, are critical for securing sustainable energy supply and reducing carbon emissions (Muneer et al., 2006; Farhana et al., 2022). Solar energy, in particular, has gained growing attention in recent years due to its inexhaustible, free, and clean nature.

One of the first studies in this field was conducted by Abdel-Dayem and Mohamad, who examined the potential of using solar energy as a renewable source in textile factories. Their work demonstrated that solar energy, as a clean energy source, provides significant benefits in reducing carbon dioxide emissions (Khanmohammadi et al., 2022). Other renewable energy applications in textile manufacturing include solar thermal systems for process water heating, photovoltaic panels for electricity generation, biomass boilers for steam production, and wind turbines for electricity supply (Kousar et al., 2022).

The adoption of renewable energy sources leads to immediate and significant reductions in carbon emissions (Bibi et al., 2024). To promote wider adoption, government incentives, effective regulations, and appropriate pricing schemes are essential. Solar energy offers greater flexibility compared to wind, while hydropower retains its value due to its stability and predictability. Advanced solar plants, equipped with storage systems that allow daytime energy to be used at night, can deliver more reliable service (Shehata, 2025).

2.3.2 Green Chemicals

Another important cleaner production approach is the substitution of conventional hazardous chemicals with green chemicals (de Oliveira Neto et al., 2019). Green chemicals offer safer alternatives by providing chemically tunable properties and functioning as less hazardous solvent systems compared to traditional organic media **(**Rehman and Zeng, 2012). In general, they are produced from renewable resources and are designed to be less toxic, biodegradable, and safer to use than conventional chemical substances (Choudhury, 2017). They can involve using renewable raw materials (e.g., biomass) and greener reaction media such as ionic liquids and supercritical fluids (Abdussalam-Mohammed et al., 2020).

In recent years, ionic liquids (ILs) have attracted significant attention as a novel class of environmentally benign solvents, offering promising potential in the development of sustainable technologies (Magina et al., 2021). Due to their unique physicochemical properties, ILs have been widely applied in various processes, including the synthesis of functional materials, catalysis, extraction, electrochemical applications, and gas separation (Zhu, 2025). Ongoing research continues to focus on the design and optimization of ILs tailored to specific industrial applications (Fernandes et al., 2025). ILs are often called green solvents because they have almost no vapor pressure, a low melting point, and a low viscosity (Kantouch et al., 2013; Textor et al., 2016). They are characterized as molten salts at room temperature (Chu et al., 2021). ILs are solvents of numerous types that can be designed with various combinations of cations and anions (Dalari et al., 2022). Moreover, almost a thousand ionic liquids are now known, and their core cation/anion classes are depicted in Figure 2.6 (Anceschi et al., 2025).Through the use of ionic liquids in the textile industry, negative environmental impacts, especially those related to water and chemical waste, can be minimized compared to traditional processes, providing potential benefits such as reducing chemical consumption, eliminating water use, and in some cases, providing new features (Meksi and Moussa, 2017). To make the process more sustainable and ensure circular production, ILs can be recycled and reused (Chowdhury, 2014).

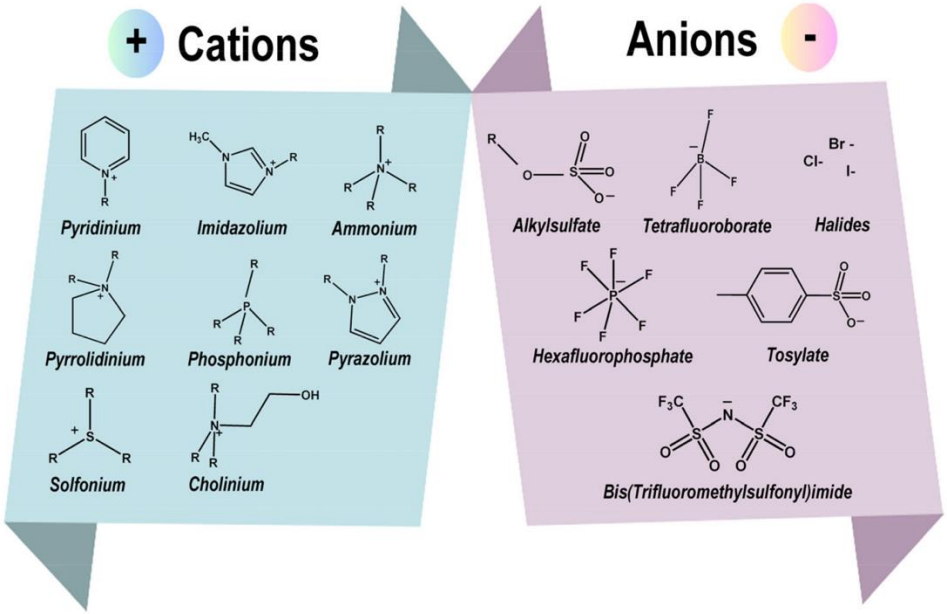


Figure 2.6 Representative structures of commonly used ionic liquid cations and anions (Anceschi et al., 2025)

Ionic liquids have also been reported to serve various auxiliary roles in textiles, functioning as decolorizers, bleaching agents, desizing agents, fiber solvents, or chemical modifiers (Chu et al., 2021). Their success in these applications is attributed not only to their intrinsic physicochemical properties, but also to their environmental advantages. For instance, the negligible volatility of ionic liquids reduces VOC emissions and contributes to safer processing conditions, while their ability to dissolve certain fiber types supports more efficient recycling and regeneration pathways compared to conventional methods (Anceschi et al., 2025). ILs therefore demonstrate potential for use across the entire textile value chain, ranging from raw fiber processing to yarn and fabric formation. Moreover, their application can reduce waste generation and enable recycling and reuse within textile wet processing systems (Saha et al., 2025).

Although ionic liquids have been explored in various areas of textile research, studies focusing on wet processing remain relatively limited and are still in a developmental phase. IL-based processes have been tested in wet processing for different fiber types, including cotton, polyester, wool, silk, and cellulose. A patent has shown that the use of ionic liquids in fiber dyeing, especially for reactive dyes, can significantly

increase the dyeing rate, and that fibers produced with IL-assisted dyeing exhibit higher colorfastness and are less prone to fading compared to those dyed with conventional salt solutions (Earle and Seddon, 2009). Yuan et al. (2010) pretreated wool fibers with 1-butyl-3-methylimidazolium chloride ([Bmim]Cl) at different temperatures prior to dyeing, enhancing dye absorption and achieving successful results. Kantouch et al. (2011) dyed wool and silk with acid and reactive dyes at low temperatures using 1-ethyl-3-methylimidazolium acetate and 1-butyl-3-methylimidazolium chloride ILs, reporting improved dyeability. Bianchini et al. (2015) developed a three-component dyeing system—pure dye (disperse dye), water, and a small amount of IL—for polyester, wool, and cotton. This method was found to be more sustainable due to minimal chemical usage and lower energy demand, with dyeing performed at 95 °C instead of 130 °C. Andrade et al. (2019) experimented with cotton dyeing using reactive dyes and 13 types of protic ionic liquids (PILs), finding improved dyeing quality compared to conventional methods. Opwis et al. (2017) compared PET dyeing with disperse dyes using conventional methods and IL-based processes, finding no significant differences in fiber structure, mechanical properties, or fastness to friction, washing, and light. Ozdemir et al. (2023) demonstrated the enhanced dyeability of cotton fabrics with reactive dyes using imidazolium- and ammonium-based ILs, while Sevindik et al. (2023) showed that PET could be dyed with four different ILs at 95 °C, further supporting ILs as a sustainable alternative.

However, there is a notable lack of comprehensive LCA studies evaluating the environmental impacts of ILs in the textile industry. Conducting such LCA-based research will be critical to fully understanding and demonstrating the sustainability potential of green chemicals in textile production. It should also be noted that the synthesis of ionic liquids involves multiple chemical steps and resource inputs, which may influence their overall environmental profile. Therefore, evaluating ILs solely based on their performance benefits during use may lead to misleading conclusions; their upstream synthesis impacts must also be considered. For this reason, recovery and reuse strategies are particularly important to ensure that ionic liquids can genuinely contribute to sustainable and circular textile production.

2.3.2.1 Recovery and Reuse of Ionic Liquids

Increased production volumes and broader implementation of ILs elevate the probability of their emission to environmental compartments. While ILs offer notable advantages across a wide range of applications due to their unique physicochemical properties, assessing their environmental fate and potential impacts remains challenging (Liu et al., 2020). Owing to their ionic nature, ILs are highly water-soluble, which raises concerns about their discharge into aquatic ecosystems (PE Macario et al., 2023). Studies have shown that certain ILs can be toxic and non-biodegradable, posing potential risks to environmental health (Mena et al., 2020).

In addition to environmental concerns, the high production cost of ILs is another important issue. Current estimates suggest that ILs are approximately 5 to 20 times more expensive than conventional molecular solvents; however, these figures are largely based on laboratory-scale assessments, which may not reflect commercial-scale realities. The overall cost is strongly influenced by the synthesis route, particularly the choice of raw materials and process conditions (Chen et al., 2014). Although there are ongoing efforts to develop more cost-effective synthesis methods and utilize lower-cost raw materials, the economic viability of ILs at an industrial scale remains a critical challenge.

To minimize the negative environmental impacts and the cost of ILs, reducing the quantity utilized in the dyeing process or recycling ILs would be an effective strategy. Research on the recovery of ionic liquids from wastewater has become particularly widespread since 2010 (Goutham et al., 2022). It is recommended that the environmental performance of IL applications be assessed using the life cycle assessment method, which considers the entire life cycle, including raw material production, application, and the recovery of ILs for reuse (Guo et al., 2023).

The recovery of ionic liquids is of critical importance due to the complexity of their synthesis and the high cost of their raw materials relative to conventional organic solvents (Meksi and Moussa, 2017). Considering both the economic value of ILs and their

potential environmental impacts, research into their recovery and reuse from wastewater is highly relevant; however, studies in this area remain quite limited (Liu et al., 2020). Methods such as distillation, extraction, adsorption, membrane filtration, and crystallization can be employed to recover ionic liquids from aqueous media. Among these methods, distillation and extraction are two of the most frequently utilized techniques (Neves et al., 2012). ILs also appear to be a viable alternative to volatile organic solvents for creating aqueous two-phase systems, a type of extraction method (Zhou et al., 2018).

Polymer/polymer, polymer/salt, or salt/salt combinations are commonly used to create the two aqueous rich phases that make up aqueous two-phase extraction (ATPE) (Nie et al., 2022). An inorganic salt solution exceeding the critical concentration is used to create a two-phase system with ionic liquids (Ferreira et al., 2014). According to the literature, K_3PO_4 and K_2HPO_4 salts have yielded successful results in the recovery of ionic liquids through the ATPE method, particularly [Bmim]Cl as well as other types of ionic liquids (Lin et al., 2020; Tanimura et al., 2019; Wu et al., 2018; Ventura et al., 2009; Pei et al., 2007; Bridges et al., 2007). These studies reported variations in the types of ionic liquids used, IL/salt/H_2O concentrations, and experimental conditions (Table 2.2). In extraction processes, systems containing IL/salt/water components have been established, and it has been reported that spontaneous phase separation occurs above a critical concentration of these components (Liu et al., 2020).

Table 2.2 Overview of published studies on the recovery of ionic liquids from aqueous media via ATPE

Ionic Liquids	Salts	IL/Salt/H2O (%)	Temperature	References
[Amim]Cl, [C_4mim]Cl	K_2HPO_4; K_2CO_3	30/15/55	45, 30, 15, and 5 °C	Tanimura et al., 2019
[C_4mim]Cl	K_3PO_4	25/15/60, 30/16/54, 35/17/48, 40/19/41, 45/21/34	-	Gutowski et al., 2003

Table 2.2 Overview of published studies on the recovery of ionic liquids from aqueous media via ATPE (continue)

Ionic Liquids	Salts	IL/Salt/H2O (%)	Temperature	References
Imidazolium-, pyridinium- and phosphonium-based ionic liquids	$Al_2(SO_4)_3$, $AlK(SO_4)_2 \cdot 12H_2O$	$Al_2(SO_4)_3$ (36%), $AlK(SO_4)_2$ (7%), ILs (90%)	298 K	Neves et al., 2012
[TBA]Pent, [TBA]Hex, [TBA]Hept, [TBA]Oct, [TBA]Dec, [TBA]Br	K_3PO_4	50/40/10	298.15 K	Basaiahgari et al., 2018
[Amim]Cl	K_3PO_4, K_2HPO_4, K_2CO_3	Variable	-	Deng et al., 2009
[C_4mim]Cl	K_3PO_4, K_2HPO_4, K_2CO_3, KOH	40% salt with different IL aqueous concentrations	-	Bridges et al., 2007
([Cn mim]BF_4, n=2,3,4), [Cn mim]Cl, n=2,4,6	K_2HPO_4, NaH_2PO_4, $(NH_4)_2SO_4$, NaCl	-	298.15 K	Wu et al., 2018
[Bmim]BF_4	Na_3PO_4, Na_2CO_3, Na_2SO_4, NaH_2PO_4, NaCl	-	298.15, 313.15, 333.15 K	Li et al., 2010
[C_4mim]Cl, [C_6mim]Cl, [C_4mim]Br, [C_6mim]Br, [C_8mim]Br, [C_{10}mim]Br	KOH, K_2HPO_4, K_2CO_3, K_3PO_4	Variable	298.15, 308.15, 318.15 K	Pei et al., 2007

Table 2.2 Overview of published studies on the recovery of ionic liquids from aqueous media via ATPE (continue)

Ionic Liquids	Salts	IL/Salt/H2O (%)	Temperature	References
[C_4mim][Br], [C_4mim]Cl; IL cations based on 1-ethyl-3-methylimidazolium and 1-butyl-3-methylimidazolium	K_3PO_4	40 wt% K_3PO_4 and ~50 wt% ILs	298 K	Ventura et al., 2009

2.3.3 Digitalization

Industry 4.0 offers significant opportunities for shifting from traditional linear economic models toward more sustainable circular economies (Rajput and Singh, 2019). At the heart of this transformation lies digitalization, which integrates advanced technologies throughout the product lifecycle (Ghobakhloo, 2020). In business processes, digitalization encompasses cloud computing, big data analytics, the Internet of Things (IoT), Artificial Intelligence (AI), and Virtual Reality (VR), enabling enhanced management and optimization of production activities (Javaid et al., 2024; Yang et al., 2023). By leveraging these tools, industries can achieve higher efficiency in product design, prototype development, and material recycling, ultimately contributing to more sustainable production by reducing resource consumption (Li et al., 2020; Happonen and Ghoreishi, 2021).

The textile and apparel industry known for its high resource consumption, waste generation, and pollution, has started adopting these technologies to address sustainability challenges (Tolentino-Zondervan and DiVito, 2024; de Oliveira Neto et al., 2022). Practices such as digital printing, 3D knitting, blockchain integration, and virtual try-on with digital avatars have become increasingly common due to their environmental and operational advantages (Rahaman et al., 2024; Rahaman and Khan, 2025). However, challenges such as the absence of an integrated digital process chain

from design to sales, high investment costs, and a shortage of specialized personnel still limit widespread adoption (de Oliveira Neto et al., 2025). If these obstacles are overcome, digitalization could offer substantial benefits, including streamlined circular economy transitions and real-time monitoring of material and product quality (Ozbek et al., 2023; de Oliveira Neto et al., 2021).

Within garment manufacturing, digital technologies are being applied across various stages from pattern creation and computerized cutting to automation, robotics, and wearable technologies (Nayak and Padhye, 2015). A key innovation is digital visualization, where 3D modeling software such as Modaris (Lectra), V-Stitcher™ (Browzwear), Pattern Design Software (Optitex), CLO 3D (Clo Virtual Fashion, Inc., 2020), and 3D Vidya (Assyst GmbH) replace traditional paper-based methods (Youn et al., 2024; Weinswig, 2016). Virtual prototyping eliminates the need for physical fabric cutting and sewing, thereby reducing material waste, minimizing production errors, accelerating timelines, and lowering costs (Huang et al., 2022; Liliana et al., 2019; Papahristou et al., 2017; Glogar et al., 2025; Chaudhary et al., 2020; Yosumaz et al., 2019).

Sample preparation, a crucial pre-production step, traditionally involves producing small quantities for approval, often generating excess fabric and accessory waste (Kamal, 2015; Tatman et al., 2022). In contrast, virtual sampling reduces physical resource usage and carbon emissions while shortening preparation time from days or weeks to hours (Spahiu et al., 2021; Pal et al., 2022; Casciani et al., 2022). Despite its potential, few studies have compared the environmental impacts of traditional and virtual sample preparation in garment manufacturing. LCA is a valuable tool to quantify such impacts, identify environmental hotspots, and evaluate alternative production methods (Bianco et al., 2022). Some studies have validated the feasibility of using AI in virtual sampling, confirming its potential contribution to sustainability (Petrak et al., 2025), yet no comprehensive LCA-based comparison currently exists.

In this thesis, the environmental benefits of virtual sample preparation in the garment sector are evaluated using the LCA approach, thereby addressing a significant

gap in the literature. Although the industrial-scale application of digital prototyping is still limited, its widespread adoption holds strong potential as an important clean production alternative in the apparel industry. By enabling more efficient resource use, reducing waste generation, and minimizing environmental impacts, digitalization supports the sustainability objectives of garment manufacturing. Thus, it is not only a technological innovation but also a strategic tool for achieving cleaner production and advancing the transition toward a more sustainable, circular textile economy.

2.3.4 Ozone Washing

Textile production, particularly wet processing, demands large volumes of water and generates wastewater with high pollutant loads. Among these wet processes, garment washing is an essential finishing process aimed at improving the appearance, handle, and comfort of apparel, especially denim and casual wear (Atav et al., 2024; Hossain et al., 2017). Traditional washing techniques, including caustic, enzyme, softener, batik, and silicone washing, are widely applied to knitted garments such as t-shirts, polo shirts, and trousers (Rouf et al., 2015). These methods frequently employ strong oxidizing agents, such as chlorine bleach, or combine enzymatic and chemical bleaching. While effective, they require substantial water, energy, and chemical inputs, resulting in high environmental burdens (Eren et al., 2020; Nergis et al., 2023). In particular, denim finishing, one of the most resource, and chemical-intensive garment washing applications, involves the intensive use of synthetic dyes, finishing agents, and oxidizing chemicals, which further contribute to water contamination and the release of hazardous substances, posing risks to aquatic ecosystems and human health (Nahid-Ull-Islam et al., 2024).

Growing environmental concerns have made water conservation and pollution reduction key priorities for transitioning the textile industry toward sustainable practices. In this context, technologies that reduce water and chemical consumption are increasingly sought after. Among emerging innovations, ozone, a strong oxidizing gas, has gained attention for its application in wet treatments such as washing, dyeing, rinsing, desizing, and scouring (Eren et al., 2020).

Ozone washing has emerged as a viable alternative that achieves faded and worn effects without the need for excessive water or toxic chemicals. It can significantly reduce water and chemical consumption, minimize pollutant loads, operate at lower temperatures and thereby save energy, and is gentler on synthetic fibers, potentially lowering microplastic release (Nahid-Ull-Islam et al., 2024; Tomšič et al., 2024). The process also shortens production time, lowers operational costs, and allows for water reuse, as no bleaching chemicals are added (Ben Fraj et al., 2021; Nayak et al., 2022; Catarino et al., 2025). Residual ozone decomposes into oxygen and water, avoiding problems linked to adsorbable organic halogens (AOX) from agents such as hypochlorite (Atav et al., 2024; Eryürük et al., 2023).

The environmental and operational benefits of ozone washing are realized in practice through its generation and application methods, which influence energy use, chemical efficiency, and fiber integrity. Industrial ozone generation is achieved via ultraviolet (UV) radiation or corona discharge applied to oxygen (O_2) (Nayak et al., 2022). The process involves filtering ambient air, concentrating oxygen, and converting it to ozone (O_3) in a generator through high-voltage discharge (Sarker et al., 2021; Atav et al., 2024). Dissolved ozone in the washing machine then acts as both a mild bleaching and sterilizing agent (Eren et al., 2020).

In the textile literature, ozonation has primarily been investigated for impurity removal, the achievement of fading effects in denim, and, in a broader context, wastewater treatment applications (Catarino et al., 2025). Nayak et al. (2022) evaluated the environmental aspects of denim washing processes and indicated that ozone-assisted techniques generally require less water and energy and are associated with reduced environmental burdens compared to conventional approaches. These observations are consistent with later findings by Atav et al. (2024), who reported comparable sustainability advantages for ozone-based denim washing under industrial conditions. However, to date, no study has systematically evaluated the environmental impacts of conventional and ozone washing processes applied to ready-made garments for aesthetic finishing from a life cycle perspective. Moreover, although previous re-

search has emphasized the potential of ozone washing to reduce water and energy consumption, most studies have relied on generalized process data rather than plant-specific operational information.

2.4 Summary of Research Gaps and Contributions

A comprehensive review of cleaner production approaches in the textile and apparel industry reveals four principal strategies that underpin sustainability-oriented transformation: the integration of renewable energy sources, the adoption of green chemical alternatives, digitalization-based innovations, and advanced washing technologies such as ozone washing. Although each of these strategies has been addressed in the existing literature, several critical research gaps remain:

- Renewable energy applications in textile manufacturing are rarely assessed through comprehensive Life Cycle Assessment (LCA) studies, limiting the quantitative understanding of their environmental benefits.
- Although ionic liquids (ILs) have attracted significant attention as promising green solvents, existing research primarily focuses on laboratory-scale performance, and systematic LCA evaluations of their large-scale applicability are still lacking.
- Although digitalization, particularly virtual prototyping and digital sample preparation, has been increasingly adopted, no LCA-based studies comparing their environmental impacts with conventional methods are currently available in the literature.
- While ozone washing has been investigated mainly in denim finishing and wastewater treatment, there is a lack of LCA studies assessing its application to ready-made garments for aesthetic finishing under real production conditions.

Within the scope of this thesis, these identified gaps are addressed by systematically evaluating the environmental performance of cleaner production alternatives through

the LCA methodology. Specifically, this study contributes to the literature by (i) examining the integration of renewable energy into textile processes, (ii) assessing the sustainability potential of ionic liquids in dyeing applications, (iii) quantifying, for the first time, the environmental impacts of virtual sample preparation compared to traditional methods in garment manufacturing, and (iv) evaluating ozone washing as a cleaner production alternative to conventional washing in ready-made garments. By bridging these gaps, this thesis not only enriches the academic understanding of cleaner production in the textile sector but also provides practical insights for guiding sustainable industry practices.

CHAPTER THREE
MATERIAL AND METHODS

3.1 Pilot Plant Description

Studies were conducted at the İzmir factory of TYH Tekstil, one of the largest garment manufacturers in Turkey, employing more than 3,000 people and having a production capacity exceeding 15 million pieces annually. The company operates a total of 12 production facilities in different locations. The company supplies products to 35 internationally recognized apparel brands across 22 countries. In addition, TYH Tekstil has R&D centers located in Istanbul and İzmir headquarters, where several research and development projects are carried out, some of which focus on sustainable production. In line with customer expectations, industry trends, and its sustainability goals, TYH Tekstil also employs 3D virtual modeling in sample production processes alongside traditional methods.

TYH Tekstil is mainly specialized in knitted garments. In TYH factories, garments are designed and produced. The ready-made fabric is cut to be ready to be sewn, and the cut fabrics are sewn and packaged. The production flow scheme of the plant is given in Figure 3.1.

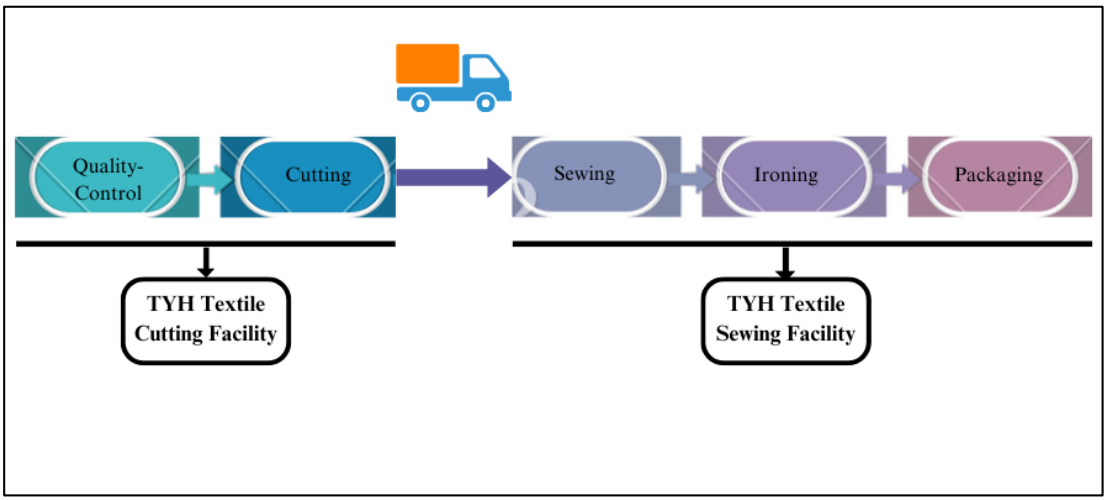


Figure 3.1 TYH Tekstil factory production flow scheme

Yarn production, fabric production, and finishing processes are not carried out within TYH factories but are instead performed by subcontractors. These stages are associated with considerable environmental burdens, including wastewater generation, process water consumption, and chemical use; therefore, TYH Tekstil is indirectly exposed to these environmental loads. Figure 3.2 illustrates the production flow scheme of knitted garments, where upstream processes are distinguished from the cutting, sewing, and packaging stages implemented in TYH factories.

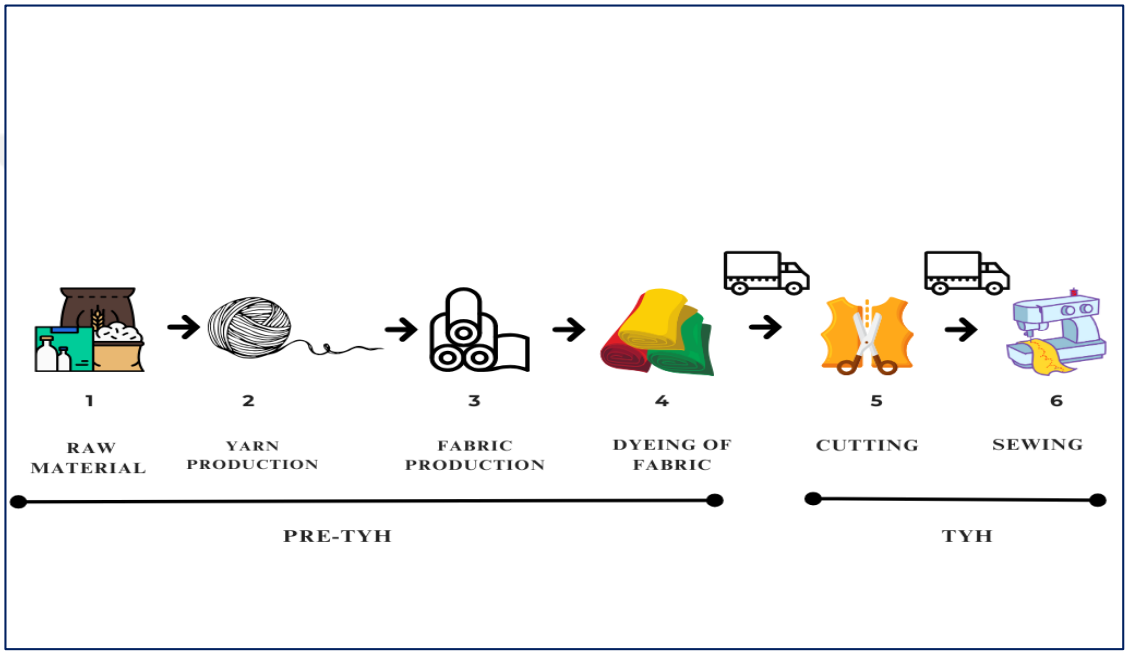


Figure 3.2 Production flow of knitted garments before and after TYH

A wide range of products is manufactured in TYH factories, with polo t-shirts, t-shirts, and sweatshirts being the most intensively produced groups. Therefore, the environmental impact assessment studies in this research have primarily focused on these product categories. As no aqueous processes are employed in the facilities, the direct environmental impacts are mainly associated with energy consumption and waste generation. The corresponding data, provided directly by TYH Tekstil in İzmir, formed the primary inputs for the life cycle assessment presented in the following sections.

3.2 LCA Studies

This research was conducted using a structured, stage-based LCA framework. In this chapter, the LCA methodology is systematically described and organized according to its main phases, with each stage developed in alignment with the relevant literature.

The LCA approach was applied in order to evaluate the environmental impacts associated with garment production processes at TYH Tekstil. The methodology was structured according to the ISO 14040 and ISO 14044 standards, which define the principles and framework of LCA studies.

In environmental assessment studies, Life Cycle Assessment (LCA) is frequently adopted as a decision-support framework to examine product systems, identify dominant processes, and compare environmentally favorable alternatives (Stainberger et al., 2009). Since the establishment of the ISO 14040 and ISO 14044 standards in 2006, the use of LCA has expanded significantly within the textile industry, particularly for evaluating the life-cycle-based environmental performance of products and services (Chen et al., 2021b). An LCA study follows a standardized structure consisting of four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Barnes et al., 2010).

In this section, the scope of the LCA study, system boundaries, functional unit, data collection methods, and impact assessment categories are described in detail. The methodological framework was tailored to the specific characteristics of knitted garment production in TYH factories.

3.2.1 Goal and Scope Definition

The goals of an LCA study are defined during the goal and scope definition phase. At this stage, the specification of the functional unit and system boundaries also constitutes an essential part of the methodological framework (Moazzem et al., 2018).

The main objective of this study is to evaluate the environmental impacts of knitted garment production processes at TYH Tekstil by applying the Life Cycle Assessment (LCA) methodology and to identify improvement potentials through different scenarios. Four alternative scenarios were considered within this framework: renewable energy utilization, digitalization applications, the use of green chemicals, and ozone washing. The results aim to provide a scientific basis for identifying environmental "hotspots" within the production system and for developing strategic recommendations toward cleaner and more sustainable production. Furthermore, the study is expected to contribute both to the academic literature and to industrial practices by serving as an example of LCA applications in the Turkish textile sector.

The scope of the study is based on evaluating the environmental performance of different scenarios at the factory scale. The LCA analyses were carried out within the cradle-to-gate framework, and the functional unit and system boundaries vary between scenarios. Therefore, the scope definitions for each scenario were addressed separately.

3.2.2 Inventory Analysis

Inventory data of the textile chain are essential to construct the life cycle model (Moazzem et al., 2018). The Life Cycle Inventory (LCI) phase is dedicated to the systematic collection of process-related data (Subramanian et al., 2020), which means that resources, energy use, and waste at each production stage must be recorded (Muthukumarana et al., 2018). Inputs include water, electricity and other energy sources, raw materials, and chemicals, while outputs consist of emissions, wastewater, solid waste, and products (Kazan et al., 2020).

In the inventory analysis, system inputs (e.g., resource and energy consumption per unit product) and outputs (e.g., wastewater, emissions, and solid waste generation per unit product) at each production stage are determined (Zhang et al., 2018). Life cycle inventory data are generally divided into two categories: primary and secondary data (Moazzem et al., 2018). Primary data consist of numerical values obtained through

direct measurement or calculations based on direct activities (Li et al., 2024). Foreground data, which are part of the primary dataset, were collected directly from the field.

When primary data were not available, the Professional Extension and Textile Finishing database within the GaBi 10.7 software was used as a source of secondary data. The GaBi databases cover a wide range of processes including power generation, raw and process materials, and transportation, thereby providing reliable secondary LCI data for modeling purposes. All data represent the years 2023 and 2024.

3.2.3 Sensitivity Analysis

Sensitivity analyses are conducted to evaluate the influence of methodological assumptions on the study outcomes (Busi, 2016). The objective of such analyses is to assess whether the results, aligned with the study's goals, are significantly affected by variations in underlying assumptions and input data. In this study, sensitivity analyses were performed for selected impact categories in accordance with the methodology defined by ISO 14044 (Schulz and Suresh, 2017).

The analyses were applied only to two scenarios Scenario 2 (Green Chemicals) and Scenario 3 (Digitalization) as both involve emerging technologies with higher levels of uncertainty. For the green chemical scenario, the assumptions regarding the amount of ionic liquid used in the dyeing process were tested. For the digitalization scenario, electricity consumption was identified as the primary contributor to environmental impacts during the sample production phase, and the sensitivity of the results to this factor was examined. These assessments provide valuable insights into the reliability of the LCA results and ensure that the conclusions drawn remain consistent under varying methodological assumptions.

3.2.4 Impact Assessment

In the impact assessment phase of life cycle analyses, different impact categories are considered depending on the goal and scope (Muthukumarana et al., 2018). In this

study, the selection of impact categories was based on the recommendations provided in the International Life Cycle Data System (ILCD) Handbook (Roos et al., 2015) as well as previously published LCA studies in the textile industry (Moazzem et al., 2021). In the literature, the most widely used life cycle impact assessment methods in the textile industry include Environmental Design of Industrial Products (EDIP), ReCiPe, and CML 2001(Chen, 2021).

In this study, the impact assessment phase was primarily carried out using the CML 2001 method (Guinée et al., 2002). Developed by the Institute of Environmental Sciences at Leiden University, this method provides midpoint indicators that allow for the assessment of the main environmental impacts associated with the production system.

The main impact categories considered under CML 2001 are as follows:

- Global Warming Potential (GWP 100 years, kg CO_2-eq)
- Acidification Potential (AP, kg SO_2-eq)
- Eutrophication Potential (EP, kg PO_4^{3-}-eq)
- Abiotic Resource Depletion Potential (ADP, kg Sb-eq)
- Human Toxicity Potential (HTP, kg 1,4-DCB-eq)

In all four scenarios (renewable energy, digitalization, green chemical, and ozone washing), the CML 2001 method was applied as the primary approach. However, in some cases, additional impact assessment methods were employed to more accurately capture the environmental impacts of scenario-specific dominant processes. In this way, the environmental impacts of different scenarios were presented in a more comprehensive and reliable manner. The impact assessment methods and selected impact categories applied for each scenario are summarized in Table 3.1.

Table 3.1 Selected impact assessment methods and categories for each scenario

Scenario	Impact Assessment Method(s)	Selected Impact Categories
Renewable Energy	CML 2001	ADP Elements, ADP Fossil, AP, EP, FAETP, GWP, HTP, MAETP, POCP
Green Chemical	CML 2001; AWARE	ADP Elements, ADP Fossil, AP, EP, FAETP, GWP, HTP, TETP; Water Consumption
Digitalization	CML 2001; Primary Energy Demand (PED); AWARE	GWP, HTP; Primary Energy Demand (PED); Water Consumption
Ozone Washing	CML 2001; AWARE	All impact categories; Water consumption

3.2.5 Interpretation

The interpretation phase is the final step of the Life Cycle Assessment (LCA), aiming to analyze results in line with the defined goals and scope, identify key findings, and derive meaningful conclusions and recommendations (ISO, 2006). In this stage, the results of inventory analysis and impact assessment are systematically evaluated to determine the most significant processes, called "hotspots," that contribute to the overall environmental impacts (Guinee, 2002).

The interpretation stage involves:

- identifying and explaining significant issues revealed by the LCA,
- evaluating the study's completeness, consistency, and sensitivity, and
- providing recommendations for environmental improvements (Laurent et al., 2020).

In this study, the interpretation was carried out by comparing the environmental impacts of different scenarios (renewable energy, green chemical, digitalization, and ozone washing). The analysis highlights how each scenario contributes to reducing the environmental burden of knitted garment production and provides strategic insights for cleaner and more sustainable textile manufacturing.

3.3 Scenario Development

In this thesis, the scenarios were developed based on the production processes carried out at TYH Textile factory. The main purpose of these scenarios is to identify practically applicable improvement opportunities that can reduce environmental impacts within the current production system.

- **Scenario 1 – Renewable Energy**: In this scenario, the electricity and steam used in garment manufacturing at TYH Textile are supplied from renewable sources instead of conventional grid and fossil-based fuels. The aim is to reduce greenhouse gas emissions and fossil resource dependency.

- **Scenario 2 – Use of Green Chemical (Dyeing with Ionic Liquid)**: Instead of conventional dyeing of polyester fabric, this scenario assumes the use of ionic liquids in the dyeing process. Due to their potential to operate at lower temperatures and with reduced water consumption, ionic liquids are expected to provide significant improvements in energy efficiency and chemical usage. Thus, this scenario targets the reduction of toxicity-related impacts as well as the minimization of freshwater consumption and wastewater generation.

- **Scenario 3 – Digitalization Applications (3D Modeling in Sample Production)**: In this scenario, traditional physical sample preparation at TYH Textile factory is replaced using 3D modelling techniques. By implementing digital sampling, fabric and accessory waste can be avoided, while energy and time savings are achieved. This contributes to the reduction of unnecessary resource use during the product development phase.

- **Scenario 4 – Ozone Washing**: This scenario considers the replacement of conventional garment washing methods with ozone washing technology. Conventional washing processes often involve multiple steps, high water and energy consumption, and the use of hazardous chemicals such as potassium permanganate. In contrast, ozone washing achieves the desired visual and finishing effects with significantly

lower resource consumption, reduced wastewater generation, and the elimination of toxic chemical inputs. The scenario aims to assess the environmental benefits of adopting ozone-based washing as a cleaner production alternative in garment finishing.

These scenarios were comparatively analyzed within the framework of LCA, providing insights into feasible cleaner production strategies for sustainable garment manufacturing.

3.3.1 Scenario 1 – Renewable Energy

This scenario evaluates the environmental impacts associated with the production of a single hoodie using the Life Cycle Assessment (LCA) methodology, with a particular focus on the garment manufacturing stage. Within this framework, cleaner production alternatives are explored by modifying the energy supply structure and fuel sources used in production processes. The objective is to assess the potential of renewable energy integration to reduce environmental impacts relative to conventional energy configurations.

The functional unit was defined as one hoodie (Figure 3.3). The total weight of one shipment-ready packaged product is 0.8776 kg. The same functional unit was also applied for the analysis of improvement scenarios to ensure consistency and comparability of results.

The system boundaries of this study were established according to a gate-to-gate approach, encompassing only the core production processes. As illustrated in Figure 3.1, the life cycle stages included within the boundaries comprise the cutting, sewing, and packaging operations of ready-made fabric at TYH Textile, together with the associated transportation activities. Excluded processes comprise the production of accessories, the manufacturing and maintenance of sewing and cutting machines, as well as the treatment and disposal of wastes.



Figure 3.3 Image of a hoodie

In recent years, large-scale garment manufacturers have increasingly invested in solar energy and biomass to meet their energy requirements, reflecting a global shift towards non-conventional energy sources. The installation of solar photovoltaic (PV) systems in production facilities and the replacement of petroleum-based boilers with biomass alternatives represent common practices within the industry (Muthukumarana et al., 2018). In line with global and national cleaner production initiatives, this study evaluates five alternative production scenarios for hoodie manufacturing at TYH Textile (Table 3.2).

Table 3.2 The generated scenarios

Scenario	Electricity Supply	Thermal Energy Supply	Transportation Fuel
S1–Baseline Scenario	Grid electricity	Natural gas	100% fossil fuel
S2–Use of Renewable Electricity	Solar energy	Natural gas	100% fossil fuel
S3–Use of Renewable Thermal Energy	Grid electricity	Biomass	100% fossil fuel
S4–Change in Transportation Fuel	Grid electricity	Natural gas	Biodiesel
S5–Combined Change in Energy and Fuel Sources	Solar energy	Biomass	Biodiesel

- **S1 (Baseline Scenario):** Reflects the current production practices, with grid electricity, natural gas-based steam, and fossil-fuel transportation.
- **S2 (Renewable Electricity):** Assumes replacement of grid electricity in cutting and sewing with photovoltaic (PV) solar energy, while other processes remain unchanged.
- **S3 (Renewable Thermal Energy):** Considers biomass as the source of thermal energy, while electricity and transportation follow the baseline conditions.
- **S4 (Transportation Fuel Change):** Analyzes the environmental effects of replacing fossil fuel in inter-facility transportation with rapeseed-based biodiesel, keeping other processes identical to the baseline.
- **S5 (Combined Change):** Evaluates simultaneous substitution of electricity with solar PV, thermal energy with biomass, and transportation fuel with biodiesel.

The garment manufacturing processes include the main operations such as cutting, sewing, printing, ironing, and packaging, as well as complementary processes such as lighting and ventilation of the facilities. The fabric waste rate arising from garment manufacturing, the amounts of electricity and steam consumed, and the material composition of the hoodie were determined based on primary data collected from the field.

Background processes such as electricity mix, steam generation, transportation modes, and fuel types were modeled using the *Energy* database in GaBi software. National data were applied for grid electricity and steam consumption. The Turkish grid electricity mix consists of 14% lignite, 18% hard coal, 37% natural gas, and 31% renewable sources. For steam generation, 99.36% of the natural gas used is imported.

In the case of biomass-based steam generation, the mix includes bagasse, eucalyptus, hardwood, olive residue pellets, organic and municipal waste, palm oil residues, sewage sludge, slaughterhouse waste, softwood, winter wheat straw mix, wood chips, wood pellets, and country-specific wood residues. Steam production is modeled based on biomass combustion, while the by-products of combustion such as gypsum, bottom ash, or fly ash are assumed to be reused in construction activities.

The datasets applied for the garment manufacturing processes in this study are summarized in Table 3.3.

Table 3.3 Life cycle inventory data

Inputs	Amount	Unit	Dataset
Dyed fabric	1.245	kg	From fabric production process
Electricity	3.6	MJ	TR: Electricity grid mix / TR: Electricity from photovoltaic
Steam	0.4451	kg	TR: Process steam from natural gas / TR: Process steam from biomass (solid)
Packaging, carton	0.02	kg	US: Corrugated product
Packaging, film	0.0052	kg	RER: Polyethylene film (PE-LD)
Diesel	0.00584	kg	EU-28: Diesel mix at filling station EU-28: Biodiesel based on rapeseed methyl ester (RME) at filling station

3.3.2 Scenario 2 – Green Chemical

This scenario evaluates the potential environmental improvements associated with substituting conventional disperse dyeing of polyethylene terephthalate (PET) fabric with an ionic liquid (IL)–based dyeing process. The assessment is conducted within the LCA framework in accordance with ISO 14040 and ISO 14044 standards, with a focus on the capacity of green chemical alternatives to reduce the environmental footprint of textile dyeing.

The functional unit was defined as the dyeing of 1 kg of raw PET fabric, allowing a consistent comparison between conventional and ionic liquid dyeing processes.

The system boundary was defined as gate-to-gate, encompassing only the dyeing stage of raw PET fabric. Upstream processes, including fabric production, were represented using secondary data, while downstream stages, such as garment manufacturing, use, and end-of-life treatment, were excluded from the scope of the assessment. The process flow diagram and system boundary for the evaluated dyeing alternatives are presented in Figure 3.4, illustrating both dyeing routes considered in this study.

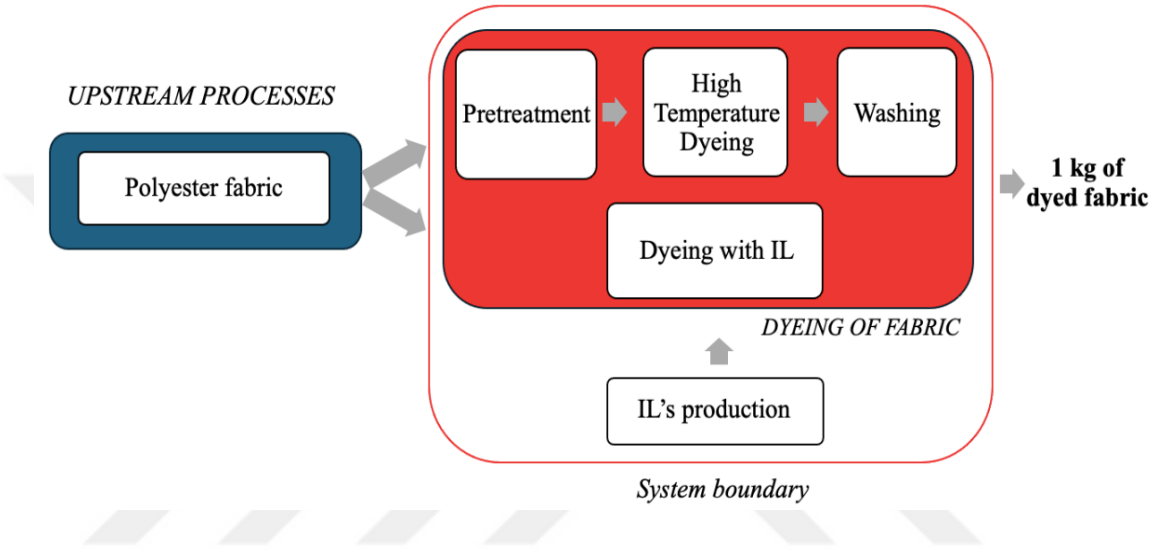


Figure 3.4 System boundary of "dyeing of 1 kg of raw fabric"

Inventory data for conventional high temperature (HT) dyeing were obtained from literature and process datasets, while data for ionic liquid dyeing were compiled from recent studies due to the absence of IL-specific datasets in LCA software. Literature-based data were integrated into the model to represent the ionic liquid dyeing process as realistically as possible. In the following sections, the detailed inventory analysis of conventional dyeing is first presented, followed by the inventory analysis of dyeing with ionic liquids.

Conventional PET dyeing typically involves three phases: (i) desizing under alkali conditions during pre-treatment, (ii) dyeing with disperse dyes at high temperature (130 °C) in a closed system, and (iii) reduction clearing using caustic soda and sodium hydrosulfite (Altay et al., 2018; Hou et al., 2013). The first process, which is the pre-treatment of data sets, is "IT: Desizing in overflow". Warp yarns are coated with sizing

agents to prevent breakage during weaving, which must be removed before dyeing (Varadarajan & Venkatachalam, 2016; Masood et al., 2013). The second process is dying. The name of this process data set is “IT: Light Disperse Dyeing in Overflow”. Dyeing is performed at 130 °C under pressure with disperse dyes in overflow machines, generally without carriers, and takes more than eight hours (Manea et al., 2020; Ketema & Worku, 2020). The amount of dye required is assumed to be 0.5% of the dry weight of the fabric. The machine used for the analyzed process is an overflow machine. In this type of machine, the fabric is gently transported by the gravitational force of the liquor overflow. After dyeing, reductive washing is applied to improve color fastness, typically using sodium dithionite and soda (Altay et al., 2018; Eren et al., 2013). The dataset used for this process is “IT: Overflow Washing”. The detailed the overall process flow is shown in Figure 3.5.

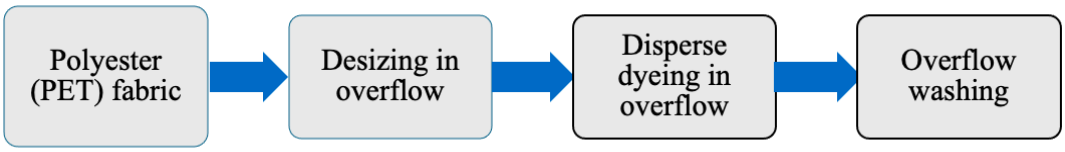


Figure 3.5 Flow chart of HT dyeing for PET fabric in GaBi software

All processes used in this modeling were created using the existing datasets of GaBi. The European Commission has recently published the *Reference Document on Best Available Techniques for the Textile Industry* (BREF), which served as the reference source for the datasets applied in this study (Joze et al., 2023). Since the database used is of industrial origin, the data quality is considered high and representative of commercial-scale processes. Accordingly, the inventory analysis, which provides the input and output data of the conventional dyeing method of 1 kg of PET fabric at industrial scale, is summarized in Table 3.4.

Table 3.4 LCI for the conventional dyeing process of PET fabric

Inputs	**Quantity**	**Unit**	**Data set**
PET fabric	1	kg	RER: Polyester (PET) fabric
Disperse dye	0.005	kg	GLO: Disperse dyes
Acetic acid	0.0134	kg	DE: Acetic acid from methanol
Dispersing agent	0.00179	kg	GLO: Dispersing agent (ethoxylate fatty alcohols)
Equalizing agent	0.00893	kg	GLO: Equalizing agent (ethoxylate amines and benzene sulphonic acid salts)
Electricity	1.43	MJ	TR: Electricity grid mix
Process steam	15.2	kg	TR: Thermal energy from natural gas
Water	26.8	kg	TR: Tap water from groundwater, TR: Water (desalinated)
Outputs			
PET fabric	1	kg	to washing
Wastewater	26.8	kg	production residues
Water	9.03	kg	Boiler feed water
Water vapor	0.476	kg	

While the conventional dyeing process of polyester fabric typically involves three distinct stages, dyeing with ionic liquids can be performed in a single step, offering a simplified and potentially more sustainable alternative. The process parameters accepted in this study were determined based on data compiled from relevant literature (Bianchini et al., 2015). According to this research, the recipes for dyeing polyester fabric with ionic liquid consisted only of disperse dye (0.5%), water and ionic liquids at different concentrations (2 g/L, 5 g/L, 15 g/L) and they used 1-Butyl-3-methylimidazolium chloride ([Bmim]Cl or [C4mim]Cl) as the ionic liquid. Additionally, since the dyeing temperature does not exceed 95 °C in ionic liquid systems, substantially lower than the 130 °C required under pressure in conventional dyeing, energy consumption is significantly reduced. Importantly, the study by Bianchini et al., 2015 demonstrated that the use of ionic liquids does not negatively affect the color quality of the dyed polyester fabrics. According to the results of the Colorfastness to Crocking Test (UNI EN ISO 105-X12/03), negligible color transfer occurred during both dry and wet rubbing. Furthermore, the color loss assessed using the gray scale for color change was also minimal, with values typically ranging from 4 to 5 on a 1–5 scale, indicating excellent color retention. These findings suggest that ionic liquid-based dyeing can

achieve comparable color performance to conventional methods. As a result, ionic liquid dyeing offers clear advantages in terms of both environmental impact and fabric color quality. Considering this information in the literature, a formulation containing 0.5% disperse dye and 5 g/L ionic liquid was chosen in this study.

Unlike laboratory-scale studies in the literature, this study evaluated the applicability of ionic liquids in industrial-scale dyeing processes. This innovative approach aims to reveal the potential environmental effects of ionic liquids not only in theoretical but also in large-scale real applications. Since the dyeing machine used in conventional dyeing on an industrial scale is an overflow machine, it was assumed that the dyeing process with ionic liquid would also take place in the same machine. According to the data set of the dyeing machine selected for 1 kg of fabric, the dyeing process takes place in batch mode. An important parameter in batch dyeing is the liquor ratio of the equipment (Joze et al., 2023). Uddin, 2021 reported the liquor ratios of the batch dyeing process in the textile dyeing industry. According to this publication, dyeing was assumed to be carried out in the overflow machine at a liquor ratio of 10:1. The calculated inputs in the dyeing process with ionic liquids at a liquor ratio of 10:1 is given in Table 3.5.

Table 3.5 LCI for dyeing with IL

Inputs	**Quantity**	**Unit**	**Data set**
PET fabric	1	kg	RER: Polyester (PET) fabric
Ionic Liquid	0.05	kg	From production of ILs
Disperse dye	0.005	kg	GLO: Disperse dyes
Electricity	0.164	MJ	TR: Electricity grid mix
Process steam	8.25	kg	TR: Thermal energy from natural gas
Water	10	kg	TR: Tap water from groundwater, TR: Water (desalinated)
Outputs			
Dyed PET fabric	1	kg	-
Wastewater	10	kg	production residues

Ionic liquid-based dyeing was modeled as an alternative to conventional polyester dyeing. Nevertheless, to ensure a comprehensive life cycle assessment, the upstream impacts associated with the production of the ionic liquid itself also need to be considered. For this reason, a cradle-to-gate inventory analysis of the ionic liquid applied in this study, 1-butyl-3-methylimidazolium chloride ([Bmim]Cl), was compiled based on data reported in the literature. The resulting inventory analysis specifies the inputs and outputs of [Bmim]Cl production, which were subsequently incorporated into the LCA model as a background process.

3.3.2.1 Ionic Liquid Production

There is insufficient data in the literature regarding the industrial-scale production of ionic liquids (ILs). Therefore, in order to establish a cradle-to-gate life cycle inventory (LCI) for the ionic liquid selected in this study, 1-butyl-3-methylimidazolium chloride ([Bmim]Cl), various approaches and assumptions were applied. For emerging chemicals such as ILs, which have complex molecular structures and multiple precursors, the life cycle tree approach has been recommended in the literature (Maciel et al., 2019). In this method, a life cycle tree is constructed by identifying all available basic precursors (e.g., ammonia, benzene, methanol), for which life cycle data are accessible. Although this approach is comprehensive, it is also time-consuming and requires step-by-step evaluation. Figure 3.6 illustrates the main chemicals involved in the synthesis of [Bmim]Cl based on the life cycle tree method.

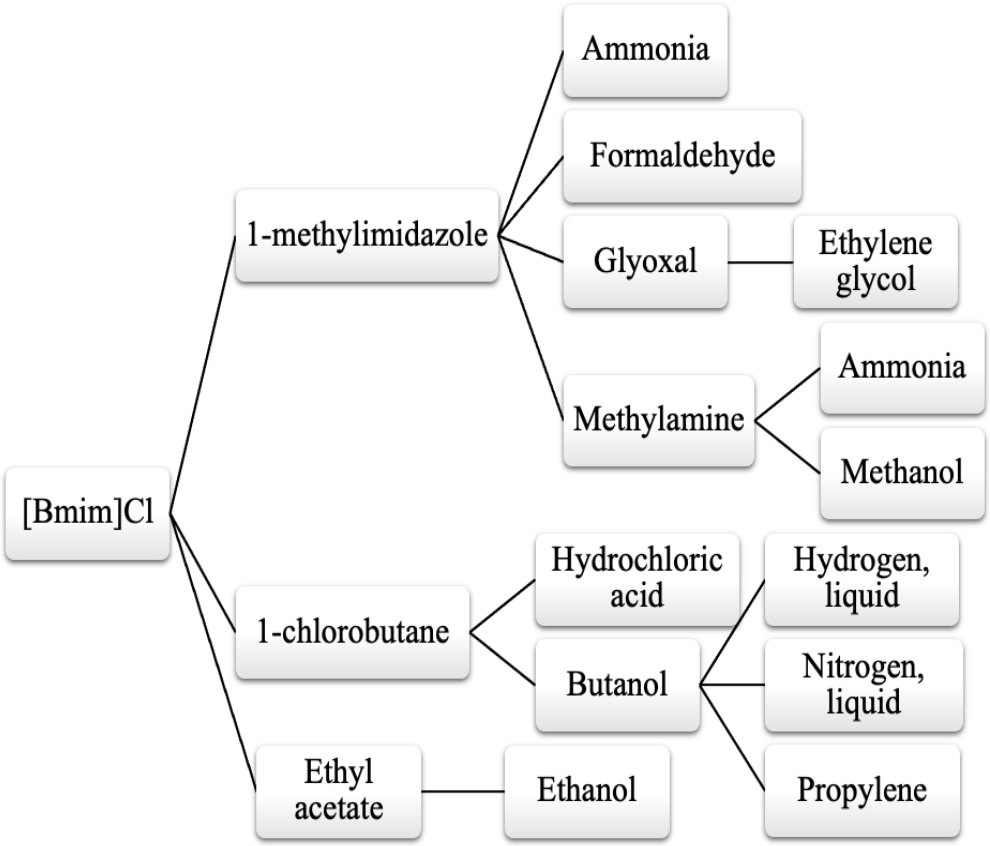


Figure 3.6 Flow diagram of the [Bmim]Cl synthesis

Neither ionic liquids nor most of the compounds used in their synthesis are available in existing LCA software databases. Therefore, inventory data regarding the production of [Bmim]Cl were compiled from published studies. Since the two main precursors of [Bmim]Cl, namely 1-chlorobutane and 1-methylimidazole, are not included in the available databases, their production processes were modeled separately using information obtained from relevant literature sources. The detailed life cycle inventory data derived from this modeling effort are summarized in Table 3.6.

Table 3.6 LCI for production of 1 kg [Bmim]Cl

Chemical compound	Quantity	Unit	Data set	References
Input				Alviz and Alvarez, 2017
Glyoxal	0.925	kg	From synthesis of glyoxal*	
Methylamine	0.199	kg	From synthesis of methylamine*	
Formaldehyde	0.518	kg	RER:Formaldehyde(HCHO;100%)	
Ammonia	0.112	kg	RER:Ammonia(NH3) production mix	
Heat	0.59	MJ	TR:Thermal energy from natural gas	
Electric energy	0.106	kWh	TR:Electricity grid mix	
Output				
N-Methylimidazole	0.391	kg	N-methylimidazole*	
Input				Mehrkesh and Karunanithi, 2016
Ethylenglycol	1.749	kg	RER:Ethylene glycol(from ethene and oxygen via EO)	
Heat	1.318	MJ	TR:Thermal energy from natural gas	
Electric energy	0.37	MJ	TR:Electricity grid mix	
Output				
Glyoxal	1	kg	Glyoxal*	
Input				Righi et al., 2011
Ammonia	0.14	kg	RER:Ammonia(NH_3)production mix, without CO_2 recovery	
Methanol	0.27	kg	-	
Heat	1.86	MJ	TR:Thermal energy from natural gas	
Electricity	0.02	MJ	TR:Electricity grid mix	
Output				
Methylamine	0.25	kg	Methylamine*	
Input				Righi et al., 2011
Butanol	0.50	kg	From synthesis of 1-butanol*	
Hydrochloric acid	0.25	kg	DE:Hydrochloric acid mix(100%)	
Heat	0.27	MJ	TR:Thermal energy from natural gas	
Electric Energy	0.08	MJ	TR:Electricity grid mix	
Output				
1-chlorobutane	0.61	kg	1-chlorobutane*	

Table 3.6 LCI for production of 1 kg [Bmim]Cl (continue)

Input				Mehrkesh and Karunanithi, 2016
N-methylimidazole	0.49	kg	From synthesis of N-methylimidazole *	
1-chlorobutane	0.61	kg	From synthesis of 1-chlorobutane*	
Ethyl acetate	0.04	kg	From synthesis of ethyl acetate	
Heat	1.5	MJ	TR:Thermal energy from natural gas	
Electric energy	0.21	MJ	TR:Electricity grid mix	
Output				
[Bmim]Cl	1	kg		
Input				Mehrkesh and Karunanithi, 2016
Propone(propylene)	0.265	kg	RER:Propene(propylene)	
Nitrogen	0.0033	kg	RER:Nitrogen (liquid)	
Hydrogen	0.011	kg	DE:Hydrogen (steam cracker)	
Process steam from light fuel oil	8.93	MJ	TR:Thermal energy from light fuel oil (LFO)	
Electric energy	0.199	MJ	TR:Electricity grid mix	
Output				
1-butanol	0.397	kg	1-butanol*	
Input				Righi et al., 2011
Ethanol	0.06	kg	DE:Ethanol(96%)	
Process steam from natural gas	0.19	MJ	TR:Thermal energy from natural gas	
Electricity	0.5	MJ	TR:Electricity grid mix	
Output				
Ethyl acetate	0.04	kg	Ethyl acetate	

3.3.2.2 Experimental Study on IL Recovery and Reuse

In addition to the ionic liquid (IL) applications carried out within the scope of this thesis, experimental studies were conducted under the Scientific Research Project (BAP) supported by Dokuz Eylül University, entitled *"Investigation of the Effect of Ionic Liquids on Sustainable Textile Production."* These studies were designed to complement the life cycle assessment of IL use in polyester dyeing. Since the large-scale synthesis of ILs requires high energy demand and significant chemical inputs, their recovery and reuse play a critical role in reducing environmental impacts and improving the economic feasibility of the process.

Within the project, four different ionic liquids were synthesized by the Department of Chemistry for polyester fabric dyeing applications:

1-butyl-3-methylimidazolium chloride ([C_4mim]Cl)

1-butyl-3-methylimidazolium bromide ([C_4mim]Br)

1,4-bis(3-methylimidazolium)butane dichloride

1,4-bis(3-methylimidazolium)butane dibromide

The synthesized ILs were tested at laboratory scale in the Department of Textile Engineering, both as solvents and pretreatment agents in PET fabric dyeing. Wastewater generated from these processes was subsequently subjected to IL recovery experiments. The aim was to determine recovery efficiency, purity of the recovered IL, and its reusability in subsequent dyeing cycles. The experimental setup was based on the aqueous two-phase extraction (ATPE) method, and the chemical stability and quality of the recovered IL were evaluated using Fourier Transform Infrared Spectroscopy (FTIR) analysis.

3.3.2.2.1 Experimental Setup

All mixtures were prepared in 50 mL Falcon tubes (Figure 3.7) and subjected to ultrasonic mixing at 40 or 50 °C (Figure 3.8). Following treatment, the samples were stored either at room temperature (24–25 °C) or under refrigerated conditions (–18 °C) for 24 h. Phase separation was subsequently evaluated by visual inspection.

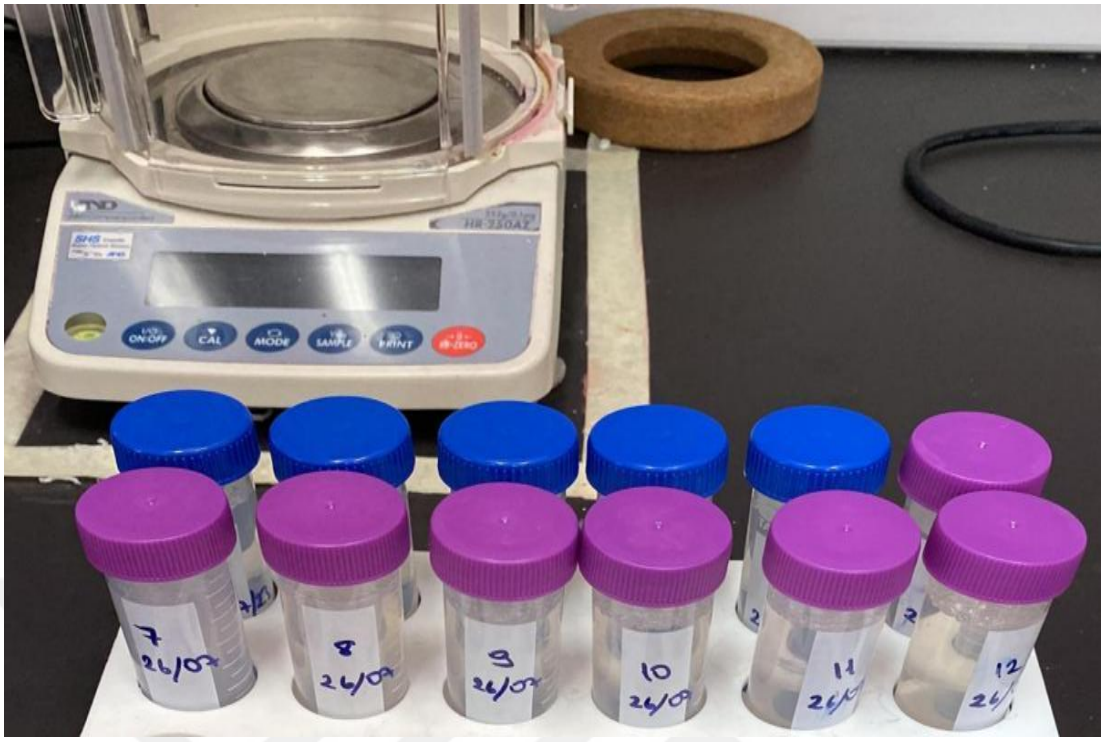


Figure 3.7 Solutions of ionic liquid, water, and salt prepared in falcon tubes (two sets stored at room temperature and in a refrigerator for 24 h)

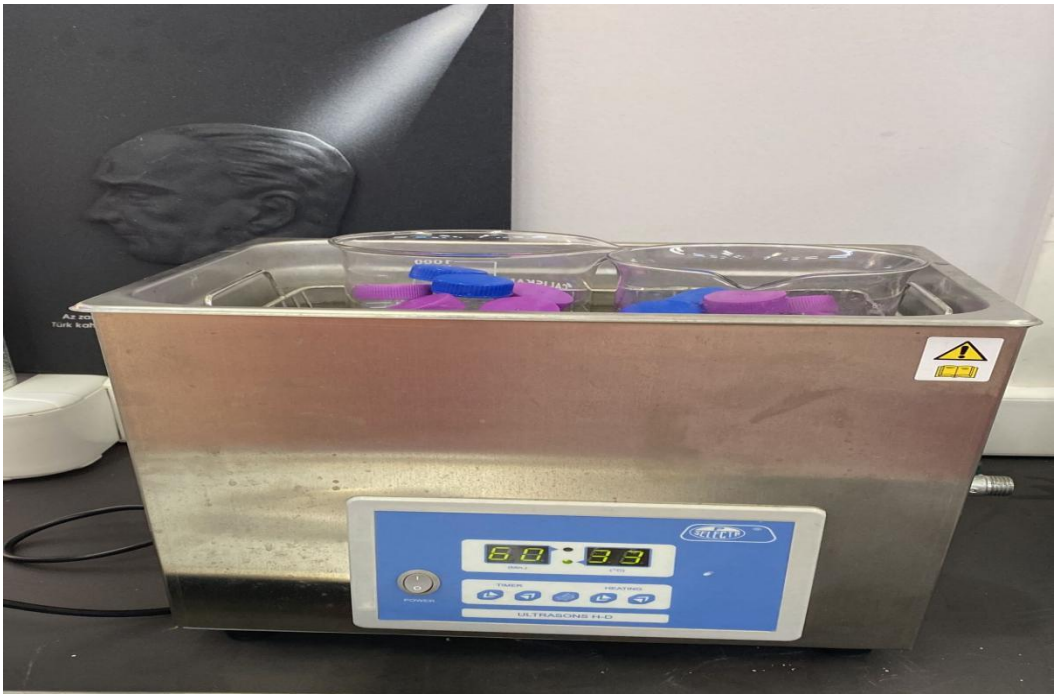


Figure 3.8 Mixing solutions in an ultrasonic bath

In the preliminary trials conducted within this study, hydrophilic ILs were evaluated for their potential to form ATPE systems in the presence of inorganic salts. According to the literature, hydrophilic ILs can form ATPE in the presence of inorganic salts under suitable conditions. Since the ILs synthesized in this study are hydrophilic, ATPE was selected as the recovery method. This approach enables simple, single-step separation in which ILs preferentially partition into one aqueous phase, while salts and dye molecules remain in the other.

To establish phase formation, different inorganic salts (K_2CO_3, K_2HPO_4, and KH_2PO_4) were tested. Preliminary experiments aimed to determine the optimum IL/salt/H_2O ratios required for efficient biphasic separation:

- For monocationic ILs ([C_4mim]Cl and [C_4mim]Br), 10% and 20% (w/v) aqueous solutions were first tested, but no clear separation was observed. Concentrations were then increased up to 30%.
- For dicationic ILs (1,4-bis(3-methylimidazolium)butane dichloride and dibromide), an initial solid IL amount of 0.5 g was tested. Stable biphasic separation was only achieved when the IL amount was increased to 2 g.

The IL/salt/H_2O ratios and conditions tested are summarized in Tables 3.7 and 3.8.

Table 3.7 ATPE Experiments with [C_4mim]Cl and [C_4mim]Br

IL/Salt/H_2O (ml, incl. Triton or PEG)	Salt type	Salt solution (%)	Ultrasonic bath temperature (°C, 1 h)
30/10/60	K_2CO_3	20	40, 50
30/20/50	K_2CO_3	40	40, 50
30/10/60	K_2HPO_4	20	40, 50
30/20/50	K_2HPO_4	40	40, 50
30/10/60	KH_2PO_4	20	40, 50

Table 3.7 ATPE Experiments with [C_4mim]Cl and [C_4mim]Br (continue)

IL/Salt/H_2O (ml, incl. Triton or PEG)	Salt type	Salt solution (%)	Ultrasonic bath temperature (°C, 1 h)
30/20/50	KH_2PO_4	40	40, 50
20/20/50/10	K_2CO_3 + Triton	20, 10	40, 50
20/20/50/10	K_2HPO_4 + Triton	20, 10	40, 50
20/20/50/10	KH_2PO_4 + Triton	20, 10	40, 50
20/20/50/10	K_2CO_3 + PEG	20, 10	40, 50
20/20/50/10	K_2HPO_4 + PEG	20, 10	40, 50
20/20/50/10	KH_2PO_4 + PEG	20, 10	40, 50

Table 3.8 ATPE Experiments with 1,4-bis(3-methyl imidazolium)butane dichloride and 1,4-bis(3-methylimidazolium)butane dibromide

Salt/H_2O/(ml, incl. Triton or PEG)	Salt type	Salt solution (%)	Ultrasonic bath temperature (°C, 1 h)
10/25	K_2CO_3	20	40, 50
20/25	K_2CO_3	20	40, 50
10/25	K_2HPO_4	20	40, 50
20/25	K_2HPO_4	20	40, 50
10/25	KH_2PO_4	20	40, 50
20/25	KH_2PO_4	20	40, 50
10/25/10	K_2CO_3 + Triton	20, 10	40, 50
10/25/10	K_2HPO_4 + Triton	20, 10	40, 50
10/25/10	KH_2PO_4 + Triton	20, 10	40, 50

Table 3.8 ATPE Experiments with 1,4-bis(3-methyl imidazolium)butane dichloride and 1,4-bis(3-methylimidazolium)butane dibromide (continue)

Salt/H_2O/(ml, incl. Triton or PEG)	Salt type	Salt solution (%)	Ultrasonic bath temperature (°C, 1 h)
10/25/10	K_2CO_3 + PEG	20, 10	40, 50
10/25/10	K_2HPO_4 + PEG	20, 10	40, 50
10/25/10	KH_2PO_4 + PEG	20, 10	40, 50

In this part of the study, real textile wastewater supplied by the Department of Textile Engineering was used to assess the feasibility of ionic liquid (IL) recovery. The wastewater samples analyzed are presented in Figure 3.9. Sample (a) represents the wastewater generated after dyeing with 30 g/L [Bmim]Br and 0.5% dyestuff, whereas sample (b) corresponds to the wastewater obtained following the pretreatment process using 30% [Bmim]Br.

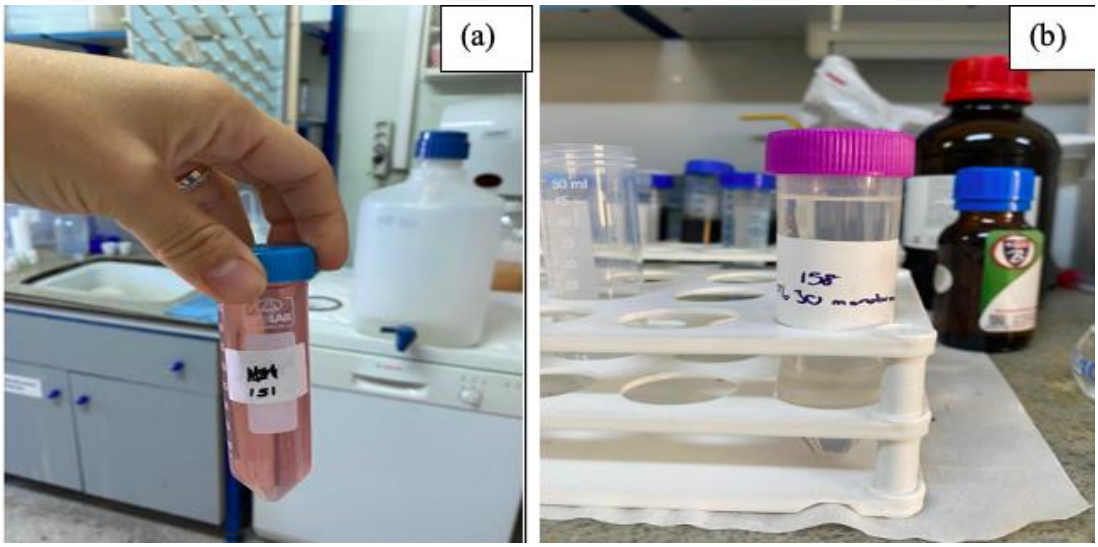


Figure 3.9 Samples of (a) wastewater with ionic liquid after dyeing and (b) wastewater with ionic liquid after pretreatment

For ATPE experiments, wastewater was mixed with 20% inorganic salt solutions under ultrasonic conditions (Figure 3.10). The general procedure involved adding wastewater and salt solution into a falcon tube, followed by mixing in an ultrasonic bath at 50 °C for one hour. Variations across samples were based on whether wastewater originated from dyeing or pretreatment and on the salt type used.

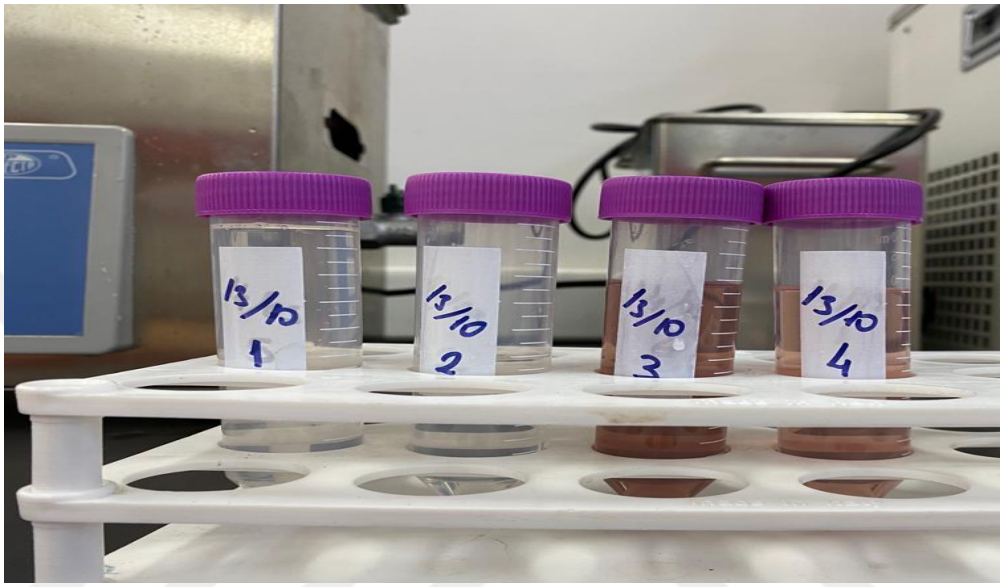


Figure 3.10 Solutions prepared with ionic liquid wastewater

Additional wastewater samples were also tested using 20% K_3PO_4 (Figure 3.11). In all cases, 15 mL of wastewater was mixed with 5 mL of K_3PO_4 solution at 40 °C for one hour. The only variations among samples were the type of IL applied during dyeing/pretreatment and its concentration (samples 02/04-1 to 02/04-8).

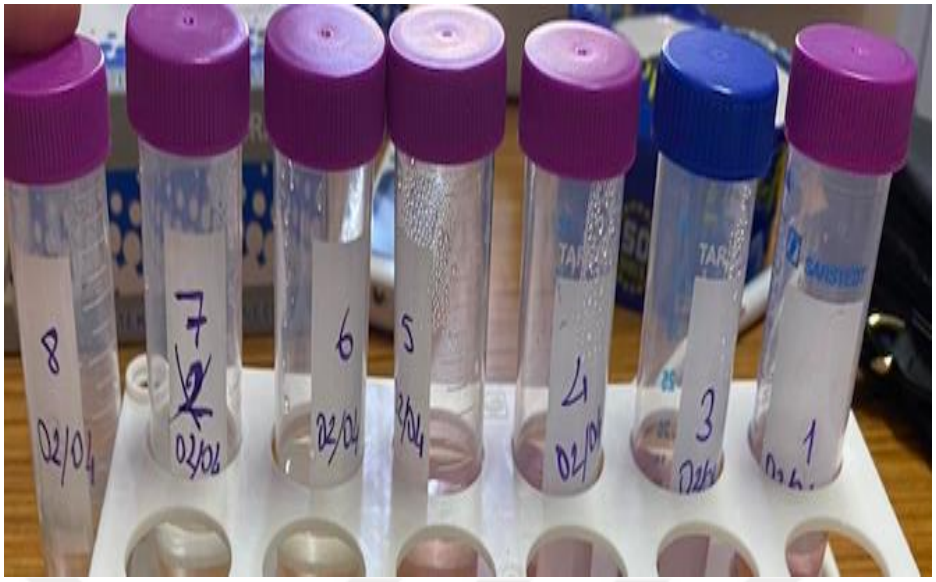


Figure 3.11 Solutions prepared with ionic liquid wastewater experimental set 2

3.3.3 Scenario 3 – Digitalization

In TYH Tekstil, sample production is carried out through both traditional methods and digital 3D modeling techniques, depending on customer requirements.

The first step of physical and virtual sample production methods is the two-dimensional (2D) pattern preparation process. Computer-aided design (CAD) software is used to create the model patterns. Then, 2D patterns are transferred to paper and sent to the cutting room for physical samples, whereas, for virtual sample production, these patterns are digitally transferred to 3D software in the .dxf format.

In traditional physical sample production, the fabrics are cut into pieces according to a 2D pattern. If there are processes such as printing or embroidery on the model, these processes are applied to the fabric pieces before the pieces are sewn together. After the final processes, such as quality control, ironing, and packaging, the samples are ready to be sent to the customer by cargo. Necessary adjustments are made according to the customer's feedback, and sometimes, the sample is produced again. These processes are repeated until approval is received from the customer, and mass production can be started only after approval is received.

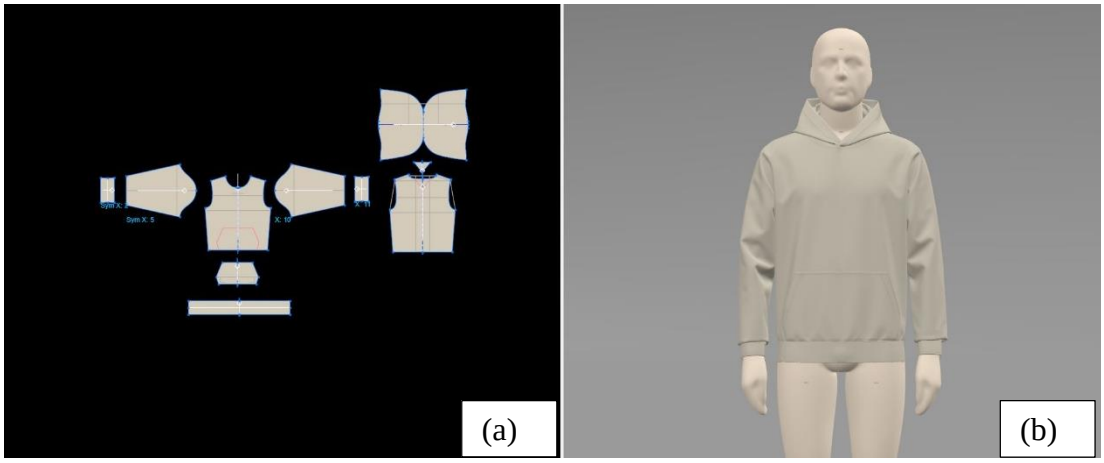


Figure 3.12 View of 2D patterns (a) and virtual samples on an avatar using 3D modeling software (b)

In digital sample production, a 50x50 cm fabric sample is first transferred to the software with the help of a fabric-digitizing device. The physical properties of the fabric (weight, thickness, bending, and stretch) are measured using a fabric analyzer device, and the fabric is then converted into virtual material (Youn et al., 2025). Fabrics are sewn virtually with the help of 3D modeling software. 2D pattern revisions can simultaneously be made on the avatar in the 3D modeling software. The virtually sewn samples are dressed in the avatar, and the necessary arrangements are made. Figure 3.7 shows the 2D patterns in the 3D modeling software and the image of the avatar wearing the product sewn with these patterns. All digital samples are the same measure as the physical sample scale. Virtual garments are sent to the customer via the online platform, and necessary corrections are made online. A comparison of the traditional and digital sampling processes carried out in the garment production plant is shown in Figure 3.8.

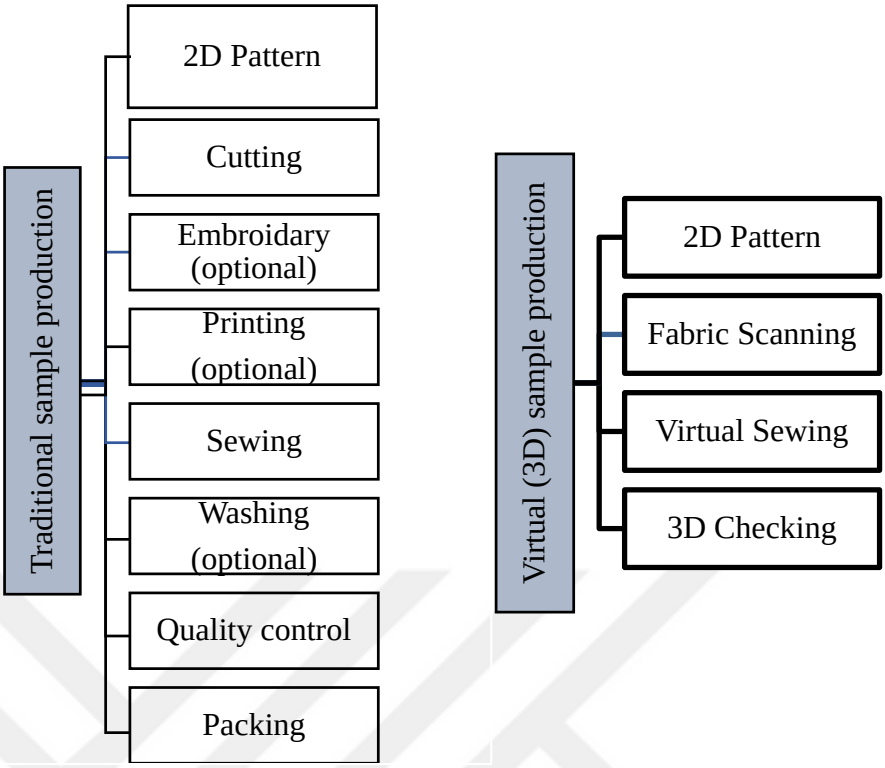


Figure 3.13 Traditional physical and virtual sample preparation flowcharts

This study aimed to determine the environmental benefits of switching from the traditional to the virtual sample preparation method as a cleaner production alternative in the garment industry. Within this context, the comparative assessment was designed to evaluate how digitalization in sample production can contribute to resource efficiency and environmental sustainability. The analysis specifically focused on the environmental implications of adopting 3D virtual sampling in place of conventional physical sampling, with the overall goal of providing insights into sustainable transformation pathways for garment manufacturing.

In this research, “one piece of garment sample” was selected as the functional unit. Eight life cycle assessments were conducted for four different garment types, namely hoodies, kids’ sweatshirts, dresses, and sweatpants. The samples were produced using both physical and virtual methods. The garments considered were a hoodie made from 50% cotton (CO)–50% polyester (PET), a kids’ sweatshirt made from 100% CO, a

dress made from 100% PET, and kids' sweatpants made from 100% CO. The front and back images of the virtual samples are given in Figure 3.14.



Figure 3.14 The front and back images of virtual samples: a) hoodie, b) kids' sweatshirt, c) dress, d) kids' sweatpants

Table 3.9 summarizes the model numbers and fabric properties of the physical samples (PS) examined in this study. A tiny piece of (50x50 cm) fabric with the same features is used to prepare a virtual sample and fabric properties such as weight and thickness are transferred to the software.

Table 3.9 Product model names and fabric properties

Model no	Product	Fabric composition	Type of fabric	Fabric Weight	Weight of one piece
PS-1	Hoodie	50% CO-50% PET	Three threads	315 gr/m^2	696.34 g
PS-2	Kids' sweatshirt	100% CO	Three threads	320 gr/m^2	471.2 g
PS-3	Dress	100% PET	Interlock	460 gr/m^2	679.58 g
PS-4	Kids' sweat-pants	100% CO	Three threads	320 gr/m^2	461.8 g

The system boundary considered in this life cycle analysis is illustrated in Figure 3.15. It was defined as cradle-to-gate, covering all processes from raw material production to the packaging of the final product for delivery. Traditional physical sample preparation includes cutting, sewing, and packaging stages, whereas digital sample preparation consists solely of 3D virtual modeling processes. The stages of traditional sample preparation implemented in the pilot plant are presented in Figure 3.16.

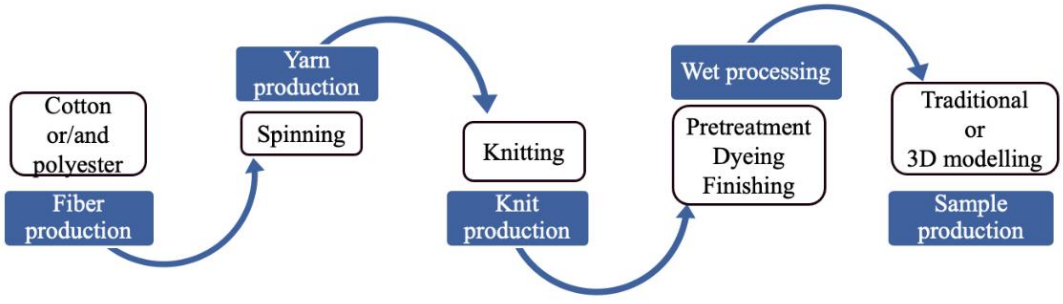


Figure 3.15 System boundary for the sample garment production

In both approaches, it was assumed that garment samples were sent to the customer for approval only once. The energy consumption of computers and software systems

used in digital sample preparation was included in the analysis. However, the environmental impacts of software development processes and hardware manufacturing (e.g., computers, digitizing devices) were excluded from the system boundary. Furthermore, the production of machinery, product labels, transportation and shipment processes, and garment accessories were also left outside the system boundaries.

In this study, foreground data within the primary data group were collected directly from the pilot plant. Whenever primary data were not available, the Textile Finishing database in the GaBi 10.7 software was used as a source of secondary data. The compiled life cycle inventory results for each garment model, considering both physical and digital sample preparation methods, are summarized in Table 3.10.

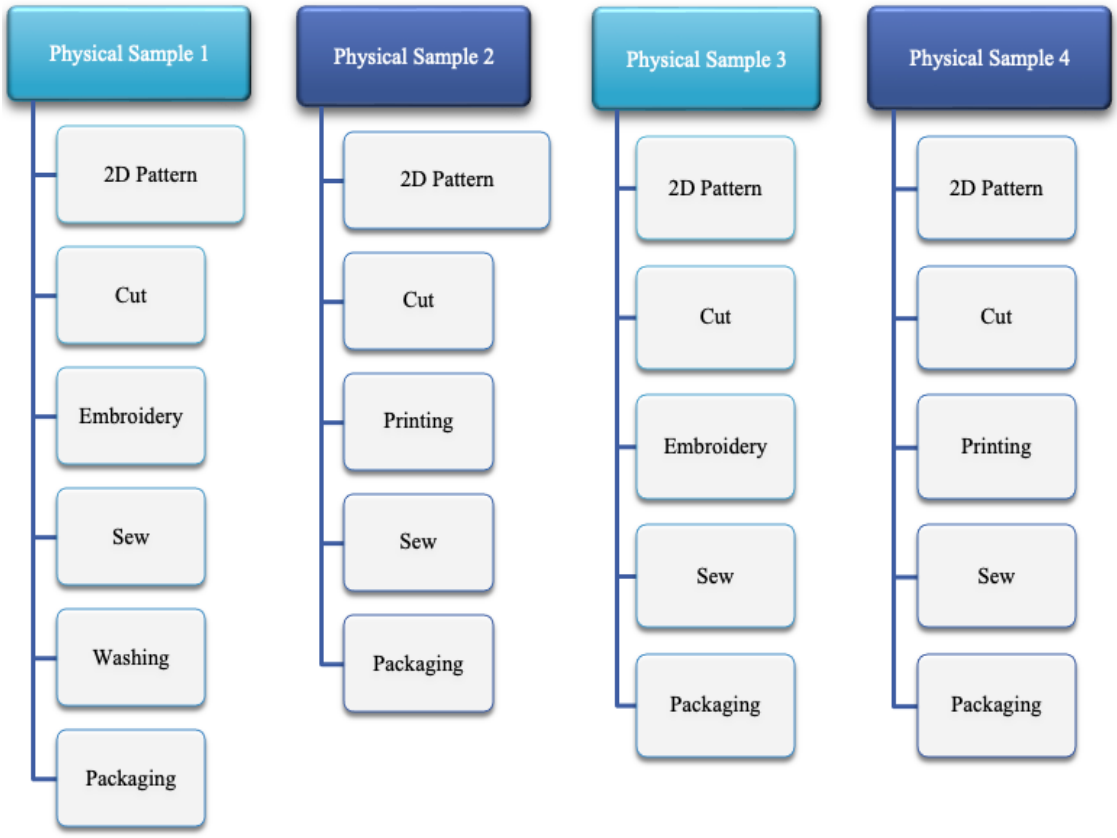


Figure 3.16 Flow diagram of traditional sample production processes for each model

Table 3.10 Life cycle inventory analysis for all models

Flow	**Unit**	**PS-1**	**VS-1**	**PS-2**	**VS-2**	**PS-3**	**VS-3**	**PS-4**	**VS-4**
Inputs									
Fabric	kg	0.87	0.075	0.589	0.078	0.85	0.142	0.616	0.078
Electricity	MJ	26.6	2.52	23.5	3.02	27.8	3.06	17	3.31
Steam	MJ	15.39	-	1.69	-	1.98	-	1.33	-
Water	kg	50	-	2.25	-	-	-	2.25	-
Corrugated board box	kg	0.012	-	0.012	-	0.012	-	0.012	-
PE film	kg	0.02	-	0.02	-	0.02	-	0.02	-
Printing paste	kg	-	-	0.09	-	-	-	0.03	-
Outputs									
Waste fabric	kg	0.696	0.075	0.471	0.078	0.68	0.142	0.462	0.078
Wastewater	kg	50	-	2.25	-	-	-	2.25	-

Raw material production, spinning, knitting, and fabric dyeing process data for both physical and digital samples were obtained from secondary data sources and modeled using the Textile Finishing database in the GaBi 10.7 software. For physical samples, primary data were collected from the pilot plant regarding the energy consumption of sewing machines during cutting and sewing operations, the steam consumption of irons, and the input/output fabric mass balance reflecting wastage during fabric cutting.

In textile production, various washing techniques are commonly applied to enhance comfort, softness, or to create a worn appearance. In this study, the washing technique applied to PS-1 was a regular cold wash, carried out at 25 °C for 25 minutes, followed by tumble-drying for 45 minutes. Data for washing, printing, and embroidery processes in physical samples were obtained directly from the field. For the washing stage,

energy and water consumption values were measured under the assumption that machines operated at minimum capacity. No detergents were used, and the drying machine was steam-powered. During the printing stage, pigment printing was applied, and the electricity consumption of the octopus-printing machine as well as the amount of printing paste were calculated per garment. In the embroidery stage, only electricity consumption was considered.

For digital samples, primary data were obtained by surveying the fabric analyzer and 3D modeling duration for each model, and electricity consumption was calculated accordingly. When fabric swatches are digitized in the 3D modeling software, only a very small amount of fabric is required, and waste generation is significantly reduced compared to physical samples.

3.3.4 Scenario 4 – Ozone Washing

In this scenario, the environmental impacts of conventional acid washing were evaluated and compared with those of an alternative oxidative treatment, namely ozone washing, applied to 100% cotton knitted fabrics. The objective of this scenario was to quantitatively determine and compare the environmental impacts arising from the substitution of a traditional chemical-based finishing process with an alternative technology. In this way, both the advantages and drawbacks of the ozone washing process, in comparison with the conventional method, were comprehensively assessed in terms of environmental performance.

The functional unit was defined as “the washing of 1 kg of knitted garment.” The knitted garment used in this study is made of 100% cotton with a pique knit structure, which is typically used for garments such as polo t-shirts. As the exact fabric weight (GSM) was not available, calculations and environmental assessments were performed based on the normalized garment weight, expressed per kilogram of product.

To ensure comparable washing effects for both ozone and conventional methods, the system boundaries were defined as gate-to-gate. The workflows of the ozone and

conventional washing processes, as implemented in the washing unit of the pilot plant used for this study, are illustrated in Figure 3.17.

The system boundaries exclude chemical transportation, as well as the production and maintenance of both ozone and conventional washing machines, and wastewater treatment. Clothes drying is also outside the scope of this study, since it is performed identically following both washing processes and does not affect the comparative assessment.

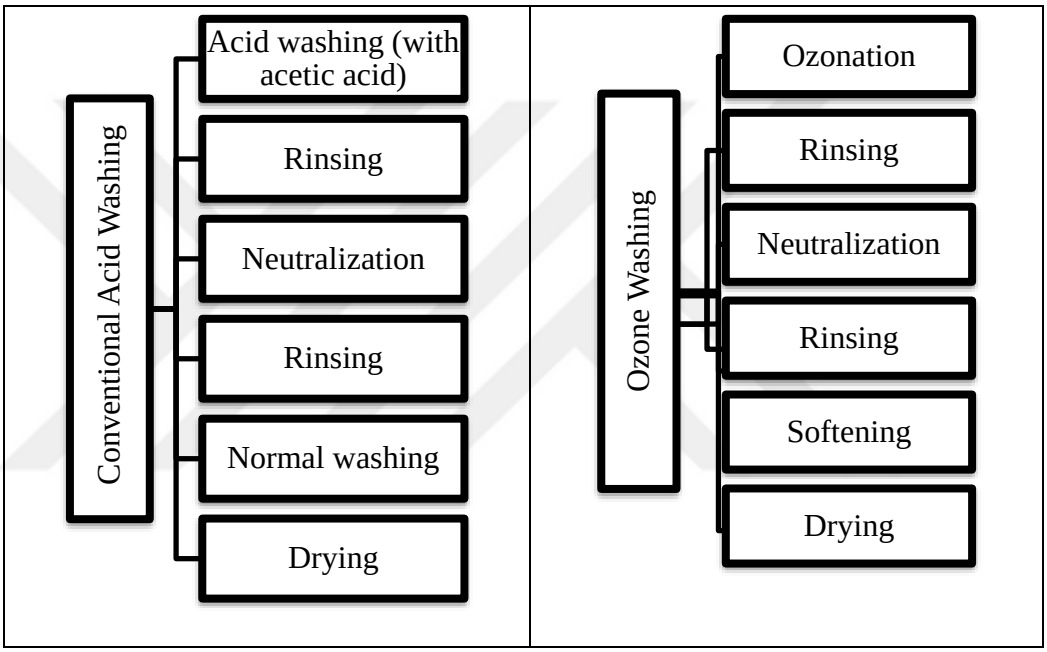


Figure 3.17 The workflows of the washing processes: (a) conventional acid washing, (b) ozone washing

The life cycle inventory (LCI) was developed for both the conventional acid washing and ozone washing scenarios, focusing exclusively on the washing stage. All inputs and outputs were normalized to the functional unit, defined as "the washing of 1 kg of cotton knitted garment". The inventory included water, electricity, thermal energy, and chemical consumption, as well as wastewater generation (Table 3.11 - 3.12).

For the conventional acid washing process, inventory data were derived from a well-established literature source (Shamsuzzaman et al., 2020). The recipe is based on a 1:5 material-to-liquor ratio (MLR), with chemical inputs of 0.2% acetic acid and 50

g/kg potassium permanganate ($KMnO_4$). A total of five bath cycles resulted in a water consumption of 25 L per kg of garment. Both electrical and thermal energy were required to operate the process. Due to database limitations, $KMnO_4$ was modeled using hydrogen peroxide (H_2O_2) as a proxy, which is widely applied as a surrogate in LCA studies.

Table 3.11 LCI of conventional (acid) washing

Input Type	**Description**	**Value**	**Unit**
Product Weight	Normalized reference: 1 kg	1.0	kg
Water Consumption	1:5 MLR ~3 bath + 2 rinse (literature assumption)	25.0	L/kg
Electricity Energy	For machine operation (pump, motor)	20.2	MJ/kg
Thermal Energy	Heating water from 25 °C to 60 °C ($\Delta T = 35°C$, 4.18 kJ/kg°C × 5 kg)	0.732	MJ/kg
Chemical – Acetic Acid	0.2% v/v	10.49	g/kg
Chemical – $KMnO_4$	-	5.0	g/kg
Chemical-Detergent	Assumed 1 g/L × 5 L	5	g/kg
Wastewater	Assumed equal to water consumption	25.0	L/kg
Chemical Residue	Moderate level – especially caution needed for $KMnO_4$	Moderate	–

For the ozone washing process, primary data were obtained from pilot plant operations. The process was performed with a 1:3 MLR and required four bath cycles, corresponding to a total water consumption of 12 L per kg of garment. Ozone gas was generated on-site using an electrically powered ozone generator, eliminating the need for thermal energy. In addition to ozone, small amounts of detergent and softener were used as auxiliary chemicals during rinsing and finishing steps. Due to commercial confidentiality, detailed process parameters cannot be disclosed; however, the normalized

data on water, energy, and chemical consumption per kilogram of fabric were fully integrated into the LCA model to ensure the reliability of the results.

Table 3.12 LCI of ozone washing

Input Type	**Description**	**Value**	**Unit**
Product Weight	Normalized reference: 1 kg	1.00	kg
Water Consumption	-	12.0	L/kg
Electricity Energy	-	21.4	MJ/kg
Thermal Energy	Not applicable (only electric process heating not included)	0.00	MJ/kg
Chemical	Softener	3.00	g/kg
Chemical	Detergent	2.00	g/kg
Oxidant (O_3)	No direct LCA data available; ozone impact accounted for within energy consumption.	Included	–
Wastewater	Assumed equivalent to water consumption	12	L/kg
Chemical Residue	Low – softener rinsed out with water	Minimal	–

CHAPTER FOUR
RESULTS AND DISCUSSION

In this chapter, the results of the Life Cycle Assessment (LCA) and experimental results are presented and discussed in detail. The findings are structured according to the scenarios defined in Chapter 3, namely renewable energy substitution, the use of green chemicals, digitalization applications, and ozone washing. For each scenario, the environmental impacts are quantified, compared, and interpreted in the context of cleaner production alternatives for the garment industry. In addition, the experimental findings related to the recovery and reuse of ionic liquids are examined. Special emphasis is placed on identifying environmental hotspots, evaluating the effectiveness of innovative approaches, and highlighting their potential contributions to sustainability in textile manufacturing.

4.1 Scenario 1 – Renewable Energy

For Scenario 1, the environmental performance of the base case hoodie production system was first evaluated and subsequently compared with alternative energy supply configurations. The Life Cycle Assessment (LCA) was conducted using a cradle-to-gate system boundary, covering raw material production, yarn and fabric manufacturing at external facilities, fabric cutting, sewing, and packaging processes at TYH Textile. Transportation stages were also included, with road transport assumed for the delivery of cotton and polyester raw materials and for the transport of dyed fabric to the garment manufacturing facility. Within this defined system boundary, the influence of renewable energy substitution on the environmental impacts of garment production was assessed relative to the current production setup.

Figure 4.1 illustrates the contribution of individual life cycle stages to the environmental impact categories calculated for the base case scenario. The results show that the majority of environmental burdens originate from raw material production and semi-finished fabric manufacturing stages. In the climate change category, the fabric knitting process is the dominant contributor, accounting for approximately 36% of the

total impact, whereas garment manufacturing represents a relatively minor share (7.2%). This elevated contribution is primarily associated with electricity consumption data reported for the knitting process. However, subsequent verification revealed that the recorded electricity consumption was overestimated, underscoring the sensitivity of process-level impact results to the quality of primary data. In a similar manner, impacts related to water scarcity and acidification are largely driven by cotton cultivation, reflecting the high water demand and intensive agrochemical use characteristic of cotton farming.

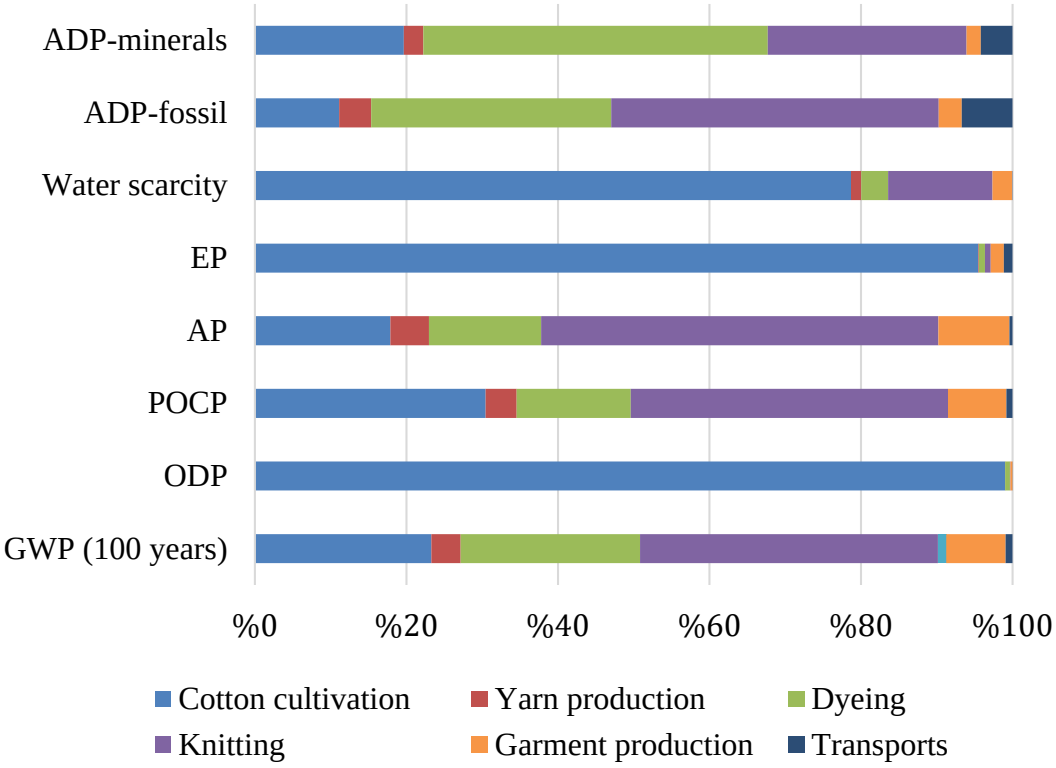


Figure 4.1 Percentage contribution of life cycle stages to environmental impact categories

These findings indicate that environmental improvement efforts in the textile and apparel sector should primarily focus on raw material and fabric production stages. Nevertheless, when the entire life cycle of the product is considered, improvements in garment manufacturing processes can also contribute to a reduction in the total environmental impacts of the product. An analysis of the garment manufacturing stage reveals that electricity and steam consumption are the most significant inputs contributing to environmental impacts. Therefore, the scenarios developed within the scope

of this thesis focus exclusively on garment manufacturing processes and aim to evaluate the improvement potentials in these stages.

As shown in Figure 4.2, the distribution of environmental impacts across the five scenarios (S1–S5) varies substantially depending on the impact category considered. This comparative assessment enables a more detailed evaluation of the relative effectiveness of the cleaner production strategies examined. In the following subsections, each impact category is analyzed individually in order to compare scenario performance and to interpret the key findings in the context of sustainable garment manufacturing.

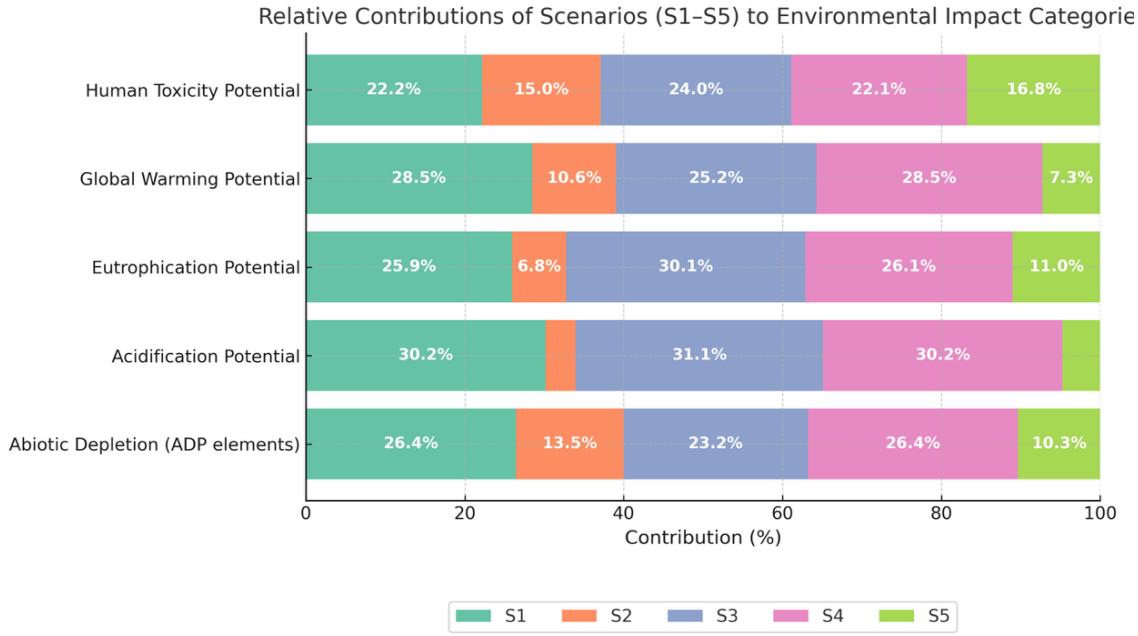


Figure 4.2 Comparison of life cycle impact analysis of all scenarios

4.1.1 Abiotic Depletion (ADP fossil)

This impact category reflects the reduction of non-renewable raw material availability on a global scale, considering a time horizon of at least 500 years. The results

demonstrate that Scenario 1 and Scenario 4 exhibit the highest abiotic depletion potentials, both calculated as 12.40 MJ (Figure 4.3). These high values can be attributed to the reliance on non-renewable energy sources in these scenarios. Scenario 3 also shows a relatively high ADP value of 10.90 MJ, though slightly lower than S1 and S4.

In contrast, Scenario 2 and Scenario 5 indicate considerably lower abiotic depletion impacts, with 6.34 MJ and 4.85 MJ, respectively. In particular, Scenario 5 achieves the most significant improvement, representing a 60.9% reduction compared to the base case (S1). This substantial decrease highlights the effectiveness of integrating renewable energy alternatives and resource-efficient practices in mitigating abiotic resource depletion. Overall, the results suggest that the transition from fossil-based to renewable energy sources plays a crucial role in reducing abiotic resource consumption in garment manufacturing processes.

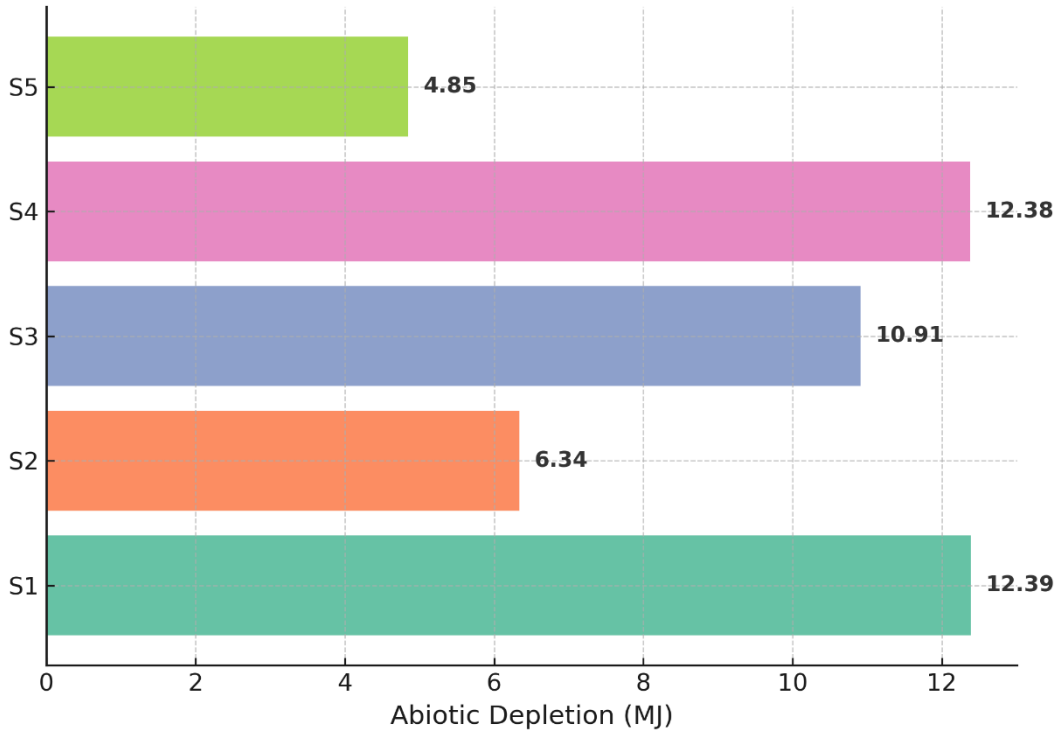


Figure 4.3 ADP-fossil impact category results

Overall, the results suggest that the transition from fossil-based to renewable energy sources plays a crucial role in reducing abiotic resource consumption in garment manufacturing processes.

4.1.2 Acidification Potential (AP)

Acidification potential is defined as the ability of certain substances to form and release H^+ ions, with sulphur dioxide (SO_2) used as the reference substance. The use of electricity, process water, and natural gas are the main contributors to acidification potential (Kazan et al., 2020). As illustrated in Figure 4.4, the results indicate that Scenario 1 and Scenario 4 present the highest acidification potential, both calculated as 7.45×10^{-3}**.** Scenario 3 also exhibits a relatively high value of 7.69×10^{-3}**,** comparable to S1 and S4. These elevated impacts can be attributed to the continued use of conventional energy sources and chemical inputs in these scenarios.

In contrast, Scenario 2 and Scenario 5 show significantly lower acidification impacts, with 9.35×10^{-4} and 1.17×10^{-3}, respectively. Particularly, Scenario 2 achieves the greatest improvement, corresponding to an 87.5% reduction compared to Scenario 1. Scenario 5 also demonstrates a substantial decrease, achieving an 84.3% reduction relative to the base case**.**

Overall, the results emphasize that integrating renewable energy sources and adopting alternative cleaner production practices can significantly mitigate acidifying emissions, thereby contributing to improved air quality and reduced environmental burden in garment manufacturing processes.

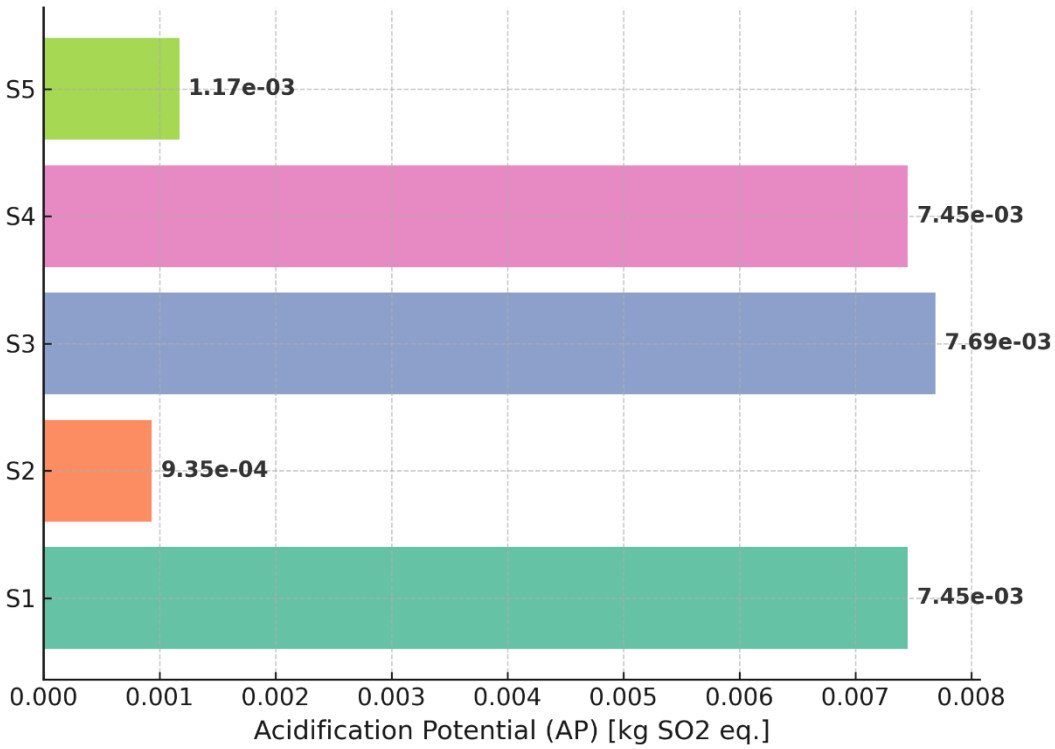


Figure 4.4 AP impact category results

4.1.3 Eutrophication Potential (EP)

Eutrophication occurs in both aquatic and terrestrial environments, mainly driven by nutrient enrichment processes. In agriculture, emissions of air pollutants, wastewater discharges, and the application of fertilizers are the primary contributors to eutrophication. This impact category is expressed in phosphate equivalents (kg PO_4^{3-} eq.). Within the textile sector, life cycle studies have shown that the agricultural phase of cotton cultivation and the dyeing processes of fabrics are the most critical stages influencing eutrophication potential. In contrast, the garment manufacturing stage contributes only marginally to EP, mainly through electricity consumption.

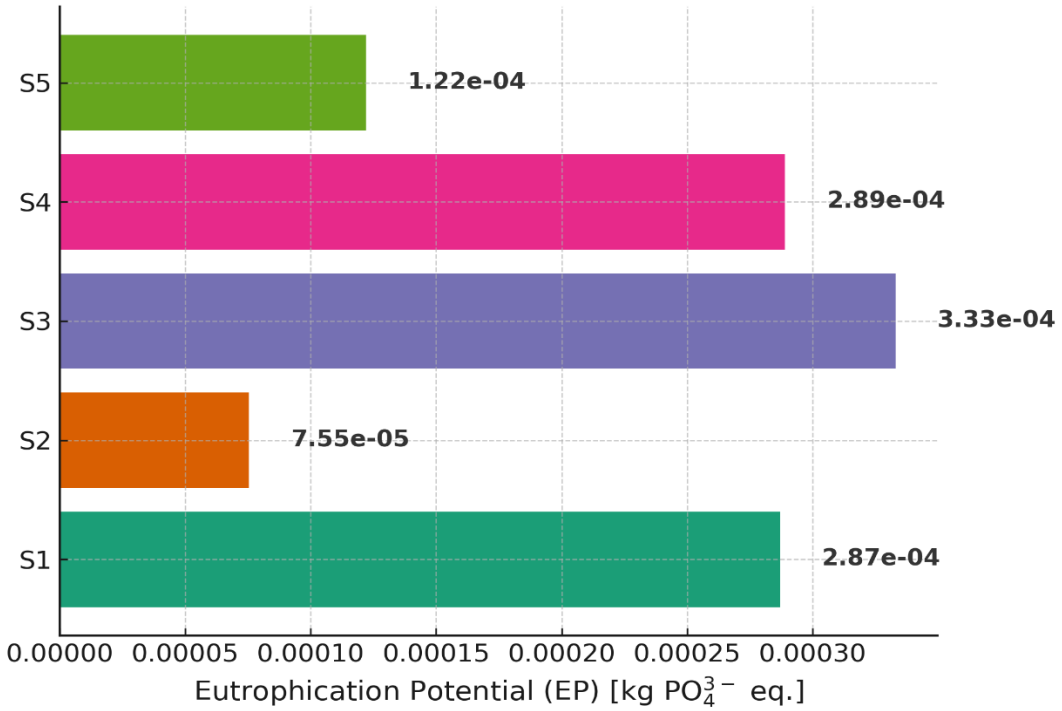


Figure 4.5 EP impact category results

As illustrated in Figure 4.5, the highest EP impacts in this study were determined for Scenario 3 (3.33×10^{-4} kg PO_4^{3-} eq.), followed closely by Scenario 4 (2.89×10^{-4} kg PO_4^{3-} eq.) and Scenario 1 (2.87×10^{-4} kg PO_4^{3-} eq.), all of which rely on grid electricity. In comparison, Scenario 2 (7.55×10^{-5} kg PO_4^{3-} eq.) achieved the lowest eutrophication potential, reflecting a 73.7% reduction compared to Scenario 1. Similarly, Scenario 5 (1.22×10^{-4} kg PO_4^{3-} eq.) demonstrated a notable improvement, corresponding to a 57.5% reduction relative to the base case. These significant decreases in S2 and S5 are directly associated with the substitution of grid electricity by renewable energy sources, particularly solar energy, and the adoption of cleaner production measures.

Taken together, the results indicate that although agricultural and dyeing stages dominate the overall eutrophication potential (EP) within the textile supply chain, improvements implemented at the garment manufacturing stage can still yield substantial reductions when renewable energy is integrated. These findings are consistent with

previous studies highlighting the role of clean energy transitions in mitigating eutrophication-related impacts in the apparel industry.

4.1.4 Global Warming Potential (GWP-100 years)

Global warming potential (GWP) is expressed in carbon dioxide equivalents (CO_2-eq.), representing the relative climate impact of a given emission compared to CO_2. The results show that the highest GWP values were obtained in Scenario 1 (0.80 kg CO_2-eq.), which represents the current situation, and Scenario 4 (0.80 kg CO_2-eq.), where only the type of fuel was changed. This similarity indicates that the contribution of transportation to overall climate impacts is negligible in this study. Instead, electricity generation is identified as the dominant contributor to greenhouse gas emissions that drive global climate change (Thompson and Duggirala, 2009).

In contrast, the scenarios based on renewable energy alternatives demonstrate significantly lower GWP results. Scenario 2 (0.30 kg CO_2-eq.) and particularly Scenario 5 (0.21 kg CO_2-eq.) achieve substantial reductions. Scenario 5, which represents the most sustainable production pathway, results in a 74.4% decrease compared to the base case (S1). Scenario 3 also yields a slightly lower GWP value (0.71 kg CO_2-eq.) than S1 and S4 but remains relatively high due to the continued reliance on conventional energy sources.

The results clearly demonstrate that transitioning to renewable energy plays a decisive role in reducing climate-related impacts in garment manufacturing. The pronounced improvement achieved in Scenario 5 illustrates the effectiveness of clean energy integration as a pathway toward sustainable textile production and lower global warming contributions (Figure 4.6).

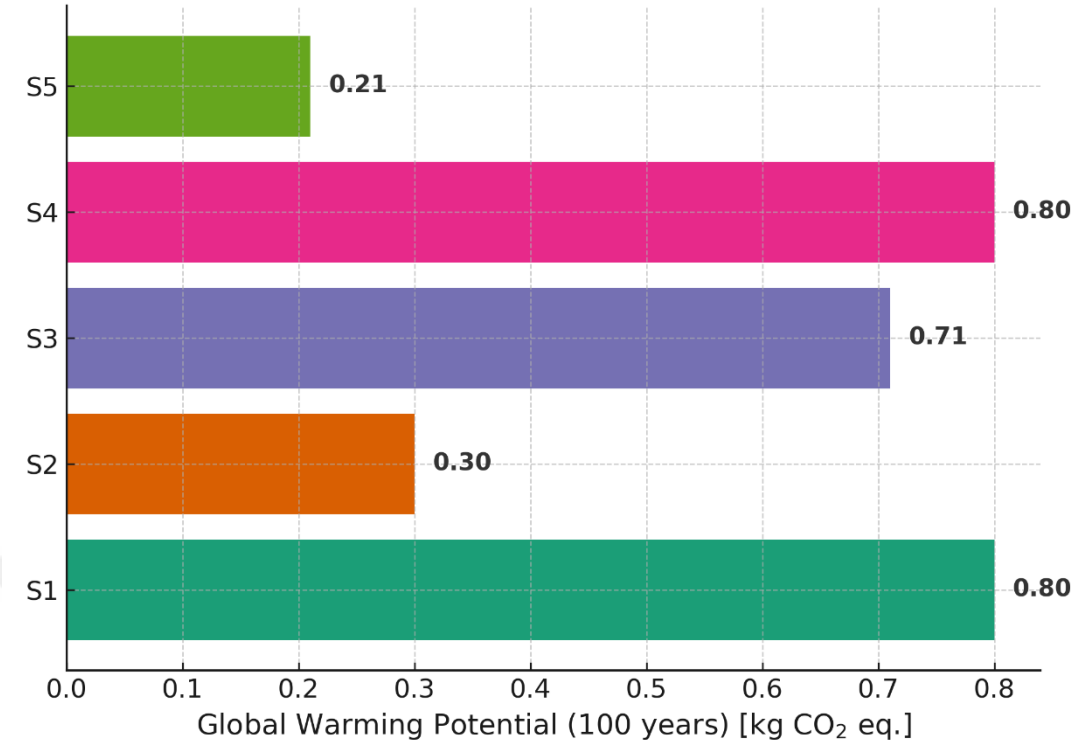


Figure 4.6 GWP-100 years impact category results

4.1.5 Human Toxicity Potential (HTP)

Human toxicity potential is mainly associated with pollutants such as particulate matter (PM), sulphur oxides (SO_x), nitrogen oxides (NO_x), and heavy metals. The results of this study indicate that the highest HTP value was obtained in Scenario 3 (6.85×10^{-2} kg 1,4-DCB eq.), where natural gas used for steam generation was replaced with biomass (Figure 4.7). Although biomass is often considered a sustainable energy source, its combustion releases SO_x, NO_x, volatile organic compounds (VOCs), and other gaseous pollutants that can deteriorate local air quality and negatively affect human health (Buyukkamaci et al., 2023).

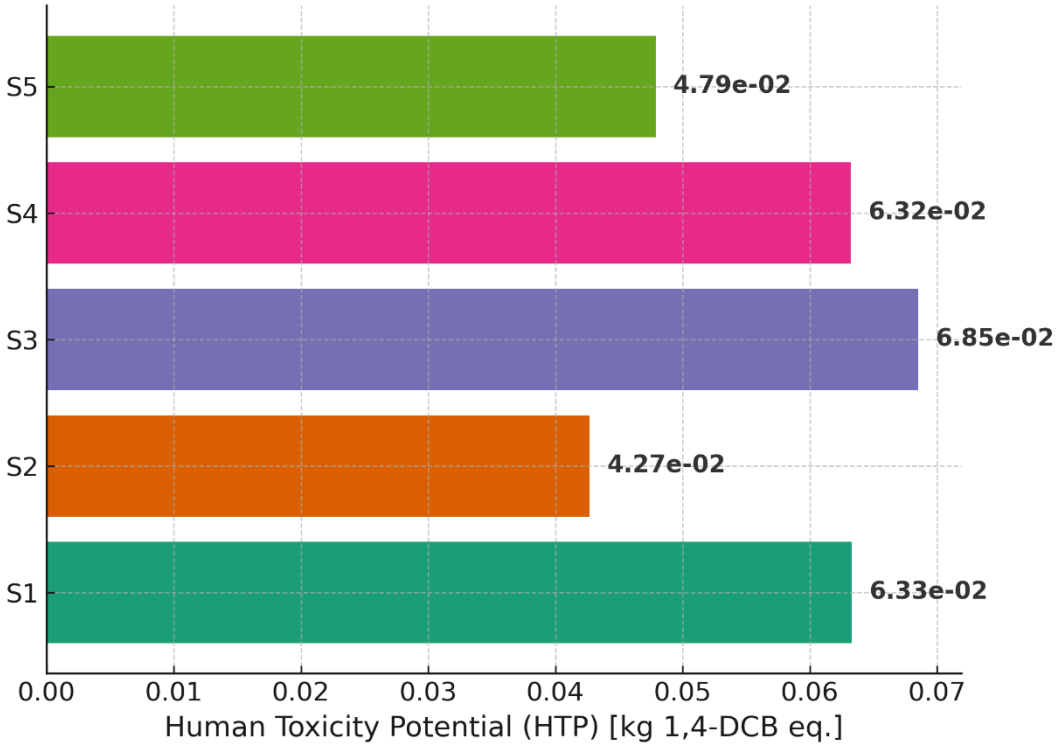


Figure 4.7 HTP impact category results

Scenarios 1 and 4 also demonstrate relatively high toxicity potentials, with values of 6.33×10^{-2} and 6.32×10^{-2} kg 1,4-DCB eq., respectively, reflecting the continued reliance on conventional energy inputs. In contrast, Scenario 2 (4.27×10^{-2} kg 1,4-DCB eq.) and Scenario 5 (4.79×10^{-2} kg 1,4-DCB eq.) exhibit lower HTP values, achieving reductions of 32.6% and 24.3%, respectively, compared to the base case (S1). These improvements are directly related to the replacement of grid electricity with renewable energy alternatives, leading to a decrease in toxic emissions.

Although renewable energy options generally improve environmental performance, the results highlight that the selection of the energy source is critical for human toxicity impacts. Biomass-based energy therefore requires careful operation and effective emission control strategies to limit potential adverse effects on human health.

4.1.6 Interpretation

The comparative analysis of all five scenarios (S1–S5) across selected environmental impact categories provides valuable insights into the improvement potentials of cleaner production alternatives in garment manufacturing. Among the scenarios, Scenario 5 emerged as the best-performing option, as it combines the use of renewable energy sources across all processes with biodiesel as the transportation fuel. Compared to the current situation (Scenario 1), Scenario 5 led to substantial reductions in global warming (74.4%), acidification (84.3%), and abiotic depletion (60.9%). These findings confirm that renewable energy integration is the most effective strategy to reduce environmental burdens in garment manufacturing.

In contrast, Scenario 3, where natural gas was substituted by biomass for steam generation, showed improvements only in abiotic depletion and global warming potential. Although biomass combustion results in direct CO_2 emissions, these are partially offset by carbon uptake during photosynthesis in biomass regrowth, thereby lowering the net global warming impact (Alma, 2022). However, biomass combustion also led to the highest human toxicity potential due to the release of SO_x, NO_x, and VOC emissions, highlighting the need for appropriate emission control measures when biomass is utilized.

The analysis further demonstrated that changing the fuel type for transportation between facilities (Scenario 4) had negligible effects on the overall environmental performance. This suggests that transportation-related impacts within the defined system boundaries are relatively minor compared to energy-related processes. Similar findings have been reported in the literature, which consistently emphasize the dominant role of electricity generation in driving global warming and acidification impacts in textile life cycle studies (Thompson and Duggirala, 2009).

Overall, this study reaffirms the well-documented evidence that renewable energy sources have considerably lower environmental impacts than fossil fuels. Transitioning to renewable electricity and clean energy alternatives enables a more sustainable

garment production pathway. Nevertheless, site-specific factors, such as land-use requirements for solar and wind installations, must be carefully considered. Rooftop solar panels installed directly on factory buildings, for instance, represent a practical and sustainable option for achieving clean energy use in the textile industry (Buyukkamaci et al., 2023).

4.2 Scenario 2 – Green Chemical

In this scenario, the environmental performance of the green chemical-based dyeing process was assessed as an alternative to the conventional high-temperature disperse dyeing used for polyester fabrics. The assessment focused on the use of ionic liquids (ILs) as environmentally friendly solvents that enable dyeing at lower temperatures and shorter durations, thereby reducing energy demand and chemical consumption.

The life cycle assessment was conducted for 1 kg of 100% PET knitted fabric within a gate-to-gate system boundary, using the CML 2001 method in line with ILCD recommendations. Selected impact categories included global warming potential (GWP), acidification potential (AP), abiotic depletion (ADP-E, ADP-F), human toxicity potential (HTP), and water consumption (WC), which together provide an integrated view of the environmental implications of replacing conventional chemicals with ionic liquids in the dyeing process.

4.2.1 Comparison of Conventional Dyeing and Dyeing with IL

To determine the changes in environmental impacts when 1 kg of 100% PET raw fabric is dyed with IL, the environmental impacts were compared with those of conventional HT dyeing. The results of both methods for each category are presented in Table 4.1, while a more comprehensive comparison is illustrated in Figure 4.8.

Table 4.1 Comparative environmental impact reductions of ionic liquid dyeing versus conventional dyeing for 1 kg of 100% PET fabric

Impact categories	**Unit**	**Dyeing with [Bmim]Cl**	**Conventional Dyeing**	**Reduction (%)**
ADP-E	kg Sb eq.	2.75E-07	6.69E-06	95.90
ADP-F	MJ	38.47	226.77	83.04
AP	kg SO_2 eq.	0.003	0.006	53.72
EP	kg PO_4 eq.	0.0005	0.002	71.32
FAETP	kg DCB eq.	0.0027	0.017	84.54
GWP-100 years	kg CO_2 eq.	2.15	7.64	71.88
HTP	kg DCB eq.	0.049	0.271	81.69
TETP	kg DCB eq.	0.0032	0.043	92.64
WC (including rainwater)	kg	12.70	114.76	88.93

Figure 4.8 shows that the environmental impacts of conventional HT dyeing are higher than those of dyeing with ionic liquid in all impact categories. In the dyeing of polyester fabric with ionic liquid, all environmental impact categories, with reductions ranging from 53.72% (AP) to 95.90% (ADP-E) were reduced by lowering the dyeing temperature from 130 °C to 95 °C, eliminating the use of dyeing auxiliaries and performing the dyeing process in a single step. The most significant improvements are observed in resource depletion (ADP-E, ADP-F), water consumption, and toxicity-related categories (FAETP, TETP, HTP). The least improvement with [Bmim]Cl dyeing process was in the acidification potential impact category with a decrease of 53.72%. This was followed by the eutrophication potential (71.32%) indicating nutrient enrichment in aquatic systems and the GWP (71.88%) indicating greenhouse gas emissions impact categories. The fact that the global warming potential and acidification potential, which are atmospheric indicators, are higher in conventional dyeing is the high-energy consumption due to dyeing polyester at high temperatures (Roy Choudhury, 2014). Disperse dyes are generally applied at high temperatures without the use of carriers in HT dyeing method (Zhang et al., 2022). PET fibers are highly crystalline and hydrophobic, necessitating heat energy to enable the dyes to permeate

the fibers (Burkinshaw, 2024). Therefore, a high amount of energy is consumed in the conventional dyeing process, leading to direct environmental effects through resource consumption and environmental emissions on ecological and human health (Palacios-Mateo et al., 2021).

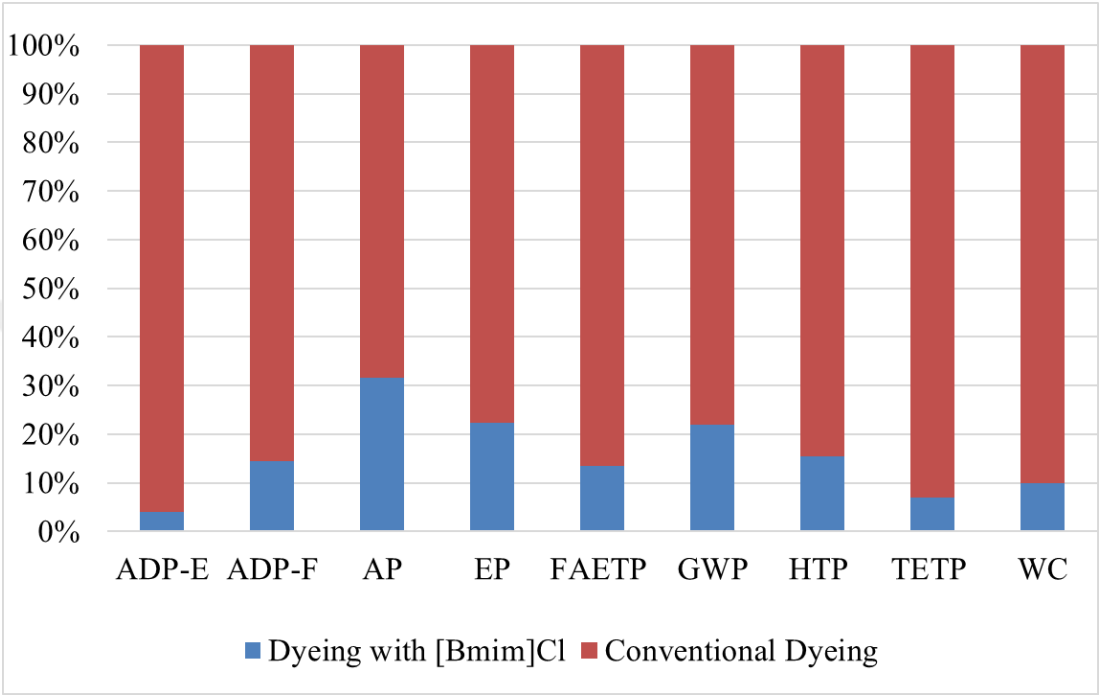


Figure 4.8 Comparison of environmental impacts of conventional dyeing and dyeing with IL

A significant reduction in environmental impacts was achieved across all toxicity indicators for the ionic liquid dyeing method. This reduction was achieved by eliminating the use of auxiliary chemicals, such as sizing agents, acetic acid, and dispersing agents, which are employed in the conventional method and have toxic properties. Conversely, the use of natural gas and electricity to heat the process baths due to the high conventional dyeing temperature is the most significant negative effect on abiotic depletion.

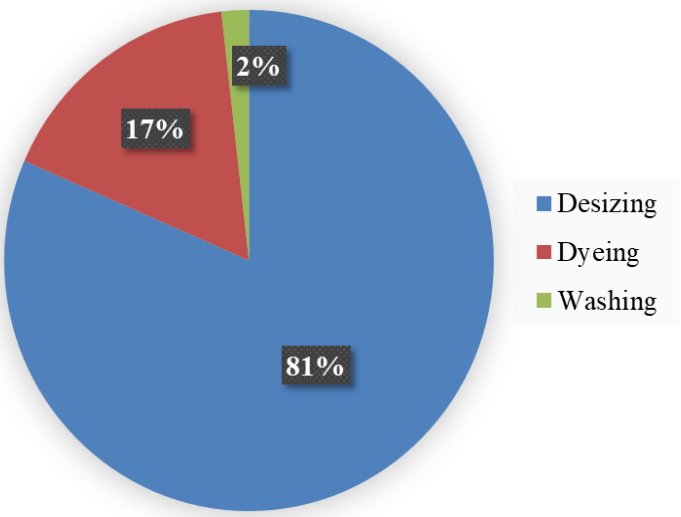


Figure 4.9 Percentage contributions of stages in the conventional dyeing process to total water consumption

A significant reduction in environmental impacts was achieved across all toxicity indicators for the ionic liquid dyeing method. This reduction was achieved by eliminating the use of auxiliary chemicals, such as sizing agents, acetic acid, and dispersing agents, which are employed in the conventional method and have toxic properties. Conversely, the use of natural gas and electricity to heat the process baths due to the high conventional dyeing temperature is the most significant negative effect on abiotic depletion.

The water consumption (WC) impact category was also taken into consideration because it is seen to be a significant factor in defining the textile industry's sustainability (Zhang et al.,2018). The dyes used in dyeing are not entirely fixed to the fabrics and are discharged with the wastewater. The amount of dye released into wastewater varies according to the type of dye and fabric, with literature reporting that 10-50% of the dye does not bind to the fabric (Jorge et al.,2023; Dutta et al.,2024). In conventional dyeing, the desizing process is one of the most water intensive unit operations. Desizing process represents four-fifths of the total freshwater consumption (Figure 4.9), as it requires a three-stage washing process with a 20:1 liquor ratio in each stage (Lara et al.,2022). While the total freshwater consumption impact category was measured as

114.76 kg in the conventional dyeing process, this impact was reduced by approximately 89% in the ionic liquid dyeing process. The primary reason for this reduction is that the ionic liquid dyeing process comprises a single step, eliminating the need for water-intensive processes such as pretreatment.

4.2.2 Ionic Liquid Production Impact Analysis

Ionic liquids may have potential adverse effects on humans and the environment due to the chemicals and solvents utilized during their synthesis (Mulushewa et al.,2021). Therefore, when evaluating the environmental compatibility of ionic liquids for any application, the life cycle study should encompass not only the ionic liquid application phase but also the synthesis of the ionic liquid (i.e., upstream processes). This will allow the development of preliminary strategies to reduce the environmental impacts of ionic liquids in case of future large-scale use (Singh and Savoy, 2020). Considering these issues, the environmental impacts of synthesis of [Bmim]Cl ionic liquid used in the dyeing of 100% PET fabric were determined in this study, and the effects of the precursor chemicals in the production of [Bmim]Cl ionic liquid are shown in Figure 4.10 for selected impact categories. The contributions of heat, electricity, and transportation used in the production of ionic liquids to these environmental impacts are included in the study but are not displayed in Figure 4.10 because their effects are negligible compared to other inputs. Accordingly, the precursor chemical with the largest environmental impact on [Bmim]Cl production in all impact categories is N-methylimidazole.

This result is consistent with the literature (Alviz and Alvarez, 2017; Mehrkesh and Karunanithi, 2016). It was observed that the production of N-methylimidazole had the highest contribution to the water scarcity impact category with a 46% and the lowest contribution to the AP impact category with a 31%. The second largest environmental impact in the synthesis of [Bmim]Cl arises from the production of glyoxal. The greatest impact in glyoxal production is on total freshwater consumption (40%), while the smallest impact is on global warming potential (19%). The production of hydrochloric

acid and ethyl acetate are the chemicals with the lowest environmental impacts in the synthesis of [Bmim]Cl.

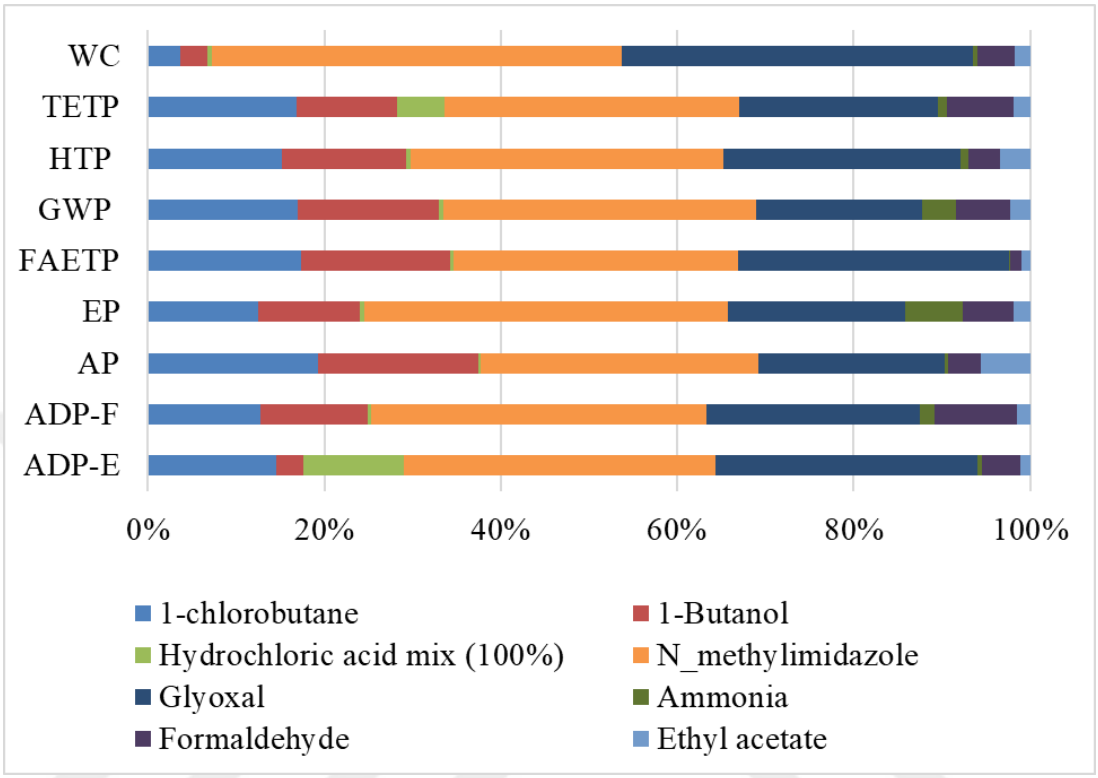


Figure 4.10 Contribution to the synthesis of [Bmim]Cl precursors' impact categories

Figure 4.11 shows the percentage contribution of precursor chemicals to the global warming potential impact category for the production of 1 kg of [Bmim]Cl. Overall, the most significant precursor chemicals in the production of [Bmim]Cl ionic liquid are N-methylimidazole ($C_4H_7N_2+$) and glyoxal. The contributions of N-methylimidazole and glyoxal to the global warming potential impact of [Bmim]Cl are 35% and 19%, respectively. This is attributed to the carbon dioxide emissions and heat utilized in the production of these precursor chemicals (Alviz and Alvarez, 2017). Since formaldehyde and glyoxal are used in the synthesis of N-methylimidazole, its contribution is high. The utilization of ethylene glycol influenced the production of glyoxal. Finally, the impact of ethyl acetate is determined by the acetic acid and ethanol it contains (Vallejos-Michea et al., 2022). Additionally, the production of these precursor chemicals contributed to the formation of emissions in air and water from fossil fuels

and energy consumption (Mehrkesh and Karunanithi,2016). Amado Alviz and Alvarez, 2017 conducted an LCA analysis to evaluate the use of [Bmim]Br as a solvent during the synthesis of a pharmaceutical product in comparison to toluene. Upon evaluating the lifecycle of [Bmim]Br production in the background series, they observed that the largest contributors to the impact categories were the production of hydrogen bromide (HBr), a precursor to 1-bromobutane, and n-butanol. It was further reported that [Bmim]Cl exhibited lower yield impacts compared to [Bmim]Br.

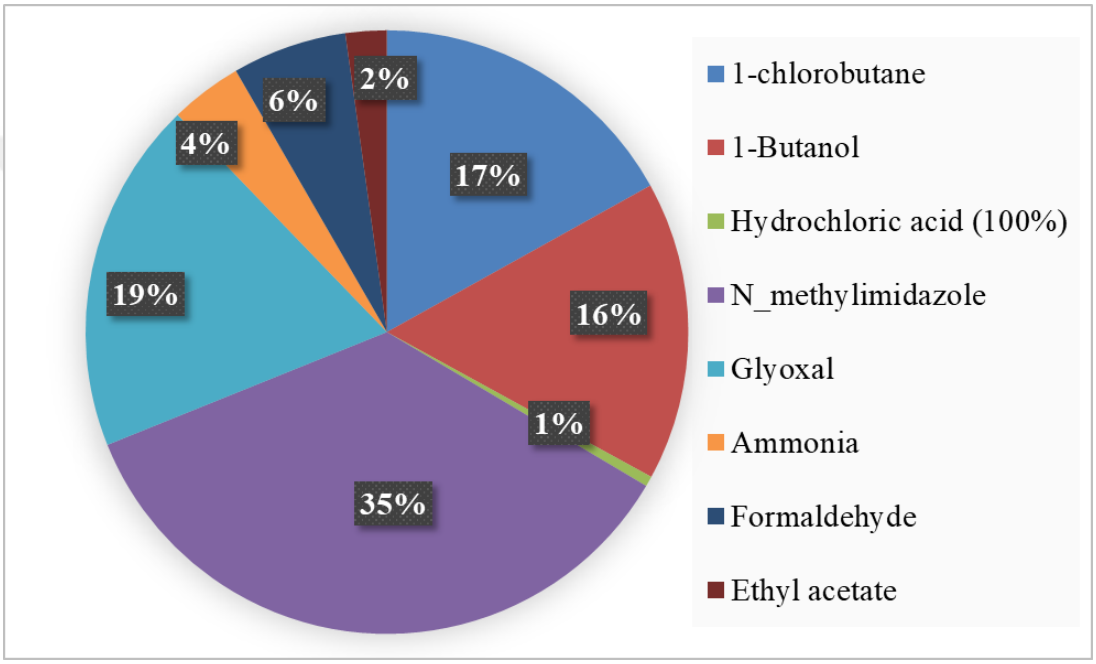


Figure 4.11 Contributions of [Bmim]Cl precursors to the GWP-100 years

4.2.3 Sensitivity Analysis for ILs

While the use of ionic liquids is recommended to mitigate the environmental impacts of textile dyeing, the synthesis of ionic liquids itself may lead to notable environmental burdens. To explore how variations in ionic liquid (IL) concentration affect overall performance, a sensitivity analysis was conducted. The baseline evaluation presented in the previous section assumed the use of 5 g/L [Bmim]Cl. For the sensitivity analysis, the environmental impacts were re-calculated for lower (2 g/L) and higher (15 g/L) IL concentrations, consistent with ranges reported in the literature.

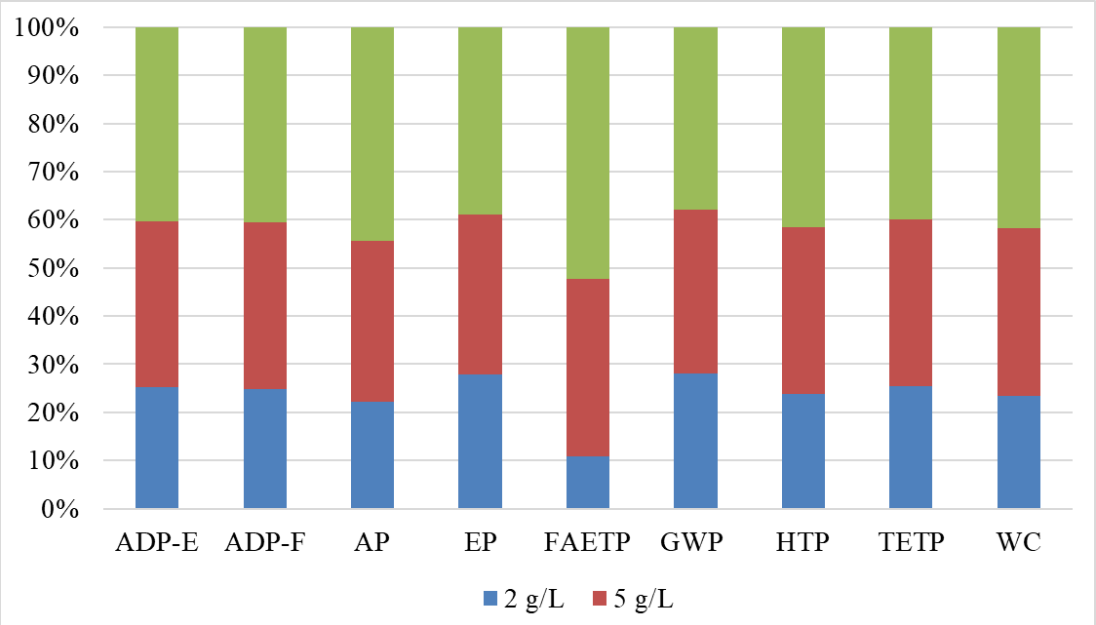


Figure 4.12 Effects of IL concentration on environmental impacts of dyeing with [Bmim]Cl

The results, illustrated in Figure 4.12, clearly show that decreasing the IL concentration from 5 g/L to 2 g/L reduces environmental impacts across all categories, whereas increasing the concentration to 15 g/L leads to higher burdens. Among the evaluated impact categories, acidification potential (AP), global warming potential (GWP), and freshwater aquatic ecotoxicity (FAETP) were identified as particularly sensitive to IL concentration. In contrast, categories such as abiotic depletion (ADP-E, ADP-F) and water consumption (WC) exhibited relatively lower sensitivity.

These findings suggest that the environmental benefits of ionic liquid–based dyeing are strongly dependent on IL concentration. Accordingly, although IL application outperforms conventional dyeing processes, concentration optimization remains essential to ensure maximum environmental benefits while avoiding unintended trade-offs.

4.2.4 Environmental impacts of IL recovery and reuse

In addition to the environmental comparison between conventional and ionic liquid (IL) dyeing processes, the recovery and reuse of ILs were also examined to evaluate their potential contribution to the overall environmental performance of the system. Since ionic liquids are relatively expensive and their synthesis processes are energy-intensive, efficient recovery and reuse can significantly reduce both environmental burdens and economic costs associated with their use in textile dyeing.

Accordingly, a separate life cycle assessment (LCA) was performed to quantitatively determine the environmental impacts of recovered and reused ILs within the dyeing process. The recovery system was modeled based on laboratory-scale experimental results. Considering the hydrophilic properties of the ionic liquid used in textile dyeing, it was assumed that the recovery was carried out through the aqueous two-phase extraction (ATPE) method. In this method, a phase separation occurs in a system consisting of ionic liquid, salt, and water components when a certain concentration is exceeded.

In the LCA model, it was assumed that 90% of the ionic liquid was recovered, while the remaining 10% was disposed of as waste. During system modeling, the energy and chemical inputs required for the ATPE and subsequent purification stages were considered. The system boundaries included both the recovery operations and the avoided production of virgin IL, allowing the identification of environmental credits achieved through the reuse of recovered material.

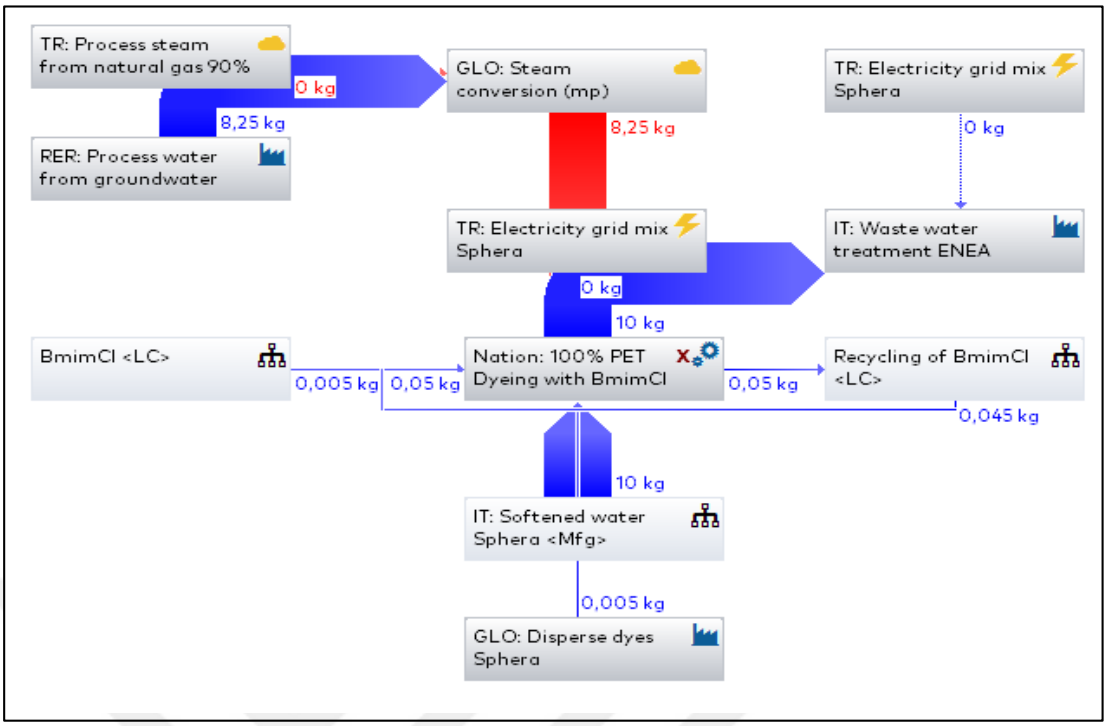


Figure 4.13 Ionic liquid recovery process modeled in LCA software

Within the scope of the life cycle analysis, the flow diagram of the IL recovery process developed for this study is presented in Figure 4.13, while the changes in environmental impacts resulting from the use of recovered IL instead of virgin IL are summarized in Table 4.2.

It was observed that the recovery of ionic liquids led to a substantial reduction across all environmental impact categories. The percentage reductions vary across impact categories despite the consistent assumption of 90% IL recovery, as each category is influenced by different factors. Notably, the freshwater aquatic ecotoxicity potential (FAETP) exhibited the most pronounced decrease, approximately 70%, when recovered [Bmim]Cl was utilized in the dyeing process. This significant reduction suggests that IL recycling effectively minimizes the discharge of ecotoxic substances into aquatic ecosystems. This is likely due to the high efficacy of recovery steps (e.g., filtration) at removing aquatic toxins associated with the spent ionic liquid. For other impact categories, reductions ranged from 4% to 33.33%. The relatively small improvement in EP (4 %) suggests that nutrient-related emissions (notably phosphorus

or nitrogen compounds) are not greatly mitigated by IL recycling. It may be that these nutrient loads originate predominantly from other process streams such as wash water or dye auxiliaries that are unaffected by [Bmim]Cl recovery.

Table 4.2 Comparison of environmental impacts between dyeing with virgin and recovered ionic liquids

Impact categories	**Unit**	**Dyeing with [Bmim]Cl**	**Dyeing with recovered [Bmim]Cl**	**% Reduction**
ADP-E	kg Sb eq.	2.75E-07	2.25E-07	18.18
ADP-F	MJ	38.47	31.10	19.16
AP	kg SO_2 eq.	0.003	0.002	33.33
EP	kg PO_4 eq.	0.0005	0.00048	4.00
FAETP	kg DCB eq.	0.0027	0.0008	70.37
GWP-100 years	kg CO_2 eq.	2.15	1.91	11.16
HTP	kg DCB eq.	0.049	0.038	22.45
TETP	kg DCB eq.	0.0032	0.0026	18.75
WC	kg	12.70	9.78	22.99

Reductions in GWP-100 (11%) and ADP-Fossil (19%) reflect energy savings associated with avoiding IL synthesis and purification, a typically energy-intensive process, by using recovered IL. Thus, the recovery and reuse of [Bmim]Cl not only decreases fossil fuel consumption but also lowers CO_2 emissions, albeit to a lesser extent than ecotoxicity-related impacts. Furthermore, the observed reductions in acidification potential (AP, 33%) and human toxicity potential (HTP, 22%) indicate that emissions of acidifying gases (e.g., SO_2, NO_x) and human-toxic compounds are also significantly mitigated through IL recovery. These improvements are consistent with the reduced demand for raw materials and the lower generation of harmful by-products.

The experimental results supporting this recovery process, including recovery yields and analytical characterizations, are presented in Section 4.5.

4.3 Scenario 3 – Digitalization

In this scenario, the environmental performance of digitalization applications in garment production was assessed. The analysis focused on the transition from conventional physical sampling to 3D virtual sampling technologies, which eliminate the need for repeated material use and process steps such as cutting, sewing, washing, and packaging. The same impact assessment method (CML 2001, August 2016) defined in the methodology section was applied to ensure consistency with other scenarios. The evaluated impact categories were Global Warming Potential (GWP 100 years), Human Toxicity Potential (HTP), Primary Energy Demand (PED), and Water Scarcity.

4.3.1 Global Warming Potential (GWP-100 years)

GWP occurs due to greenhouse gases such as carbon dioxide, nitrogen oxide, and methane in kilograms of carbon dioxide equivalent (Fidan et al., 2021). The GWP in all production processes, including the textile industry, shows the impact of production on climate change (Hackett, 2015). High energy use causes high carbon emissions in the textile industry, and the energy source used directly affects the GWP value (Niinimaki et al., 2020). In traditional physical sample production in a garment factory, high carbon emissions are produced due to high energy use, fabric waste during the cutting process, use of accessories, packaging materials, and transportation processes (Periyasamy et al., 2017). In this context, it is essential to investigate the change in the global warming potential of the samples when digital methods are used instead of physical methods in the sample preparation stage in garment factories.

Figure 4.14 illustrates the GWP 100-year results for each garment sample type. The values for physical samples (PS) were significantly higher than those for virtual samples (VS), indicating the substantial environmental advantage of virtual sampling in terms of climate impact. The highest GWP was observed in PS-1 (18.25 kg CO_2 eq.), followed by PS-3 (14.53 kg CO_2 eq.), PS-2 (7.75 kg CO_2 eq.), and PS-4 (6.89 kg CO_2 eq.). On the other hand, virtual samples ranged from 0.99 kg CO_2 eq. (VS-2) to 2.15 kg CO_2 eq. (VS-3).

The highest carbon emission was determined for PS-1 with 50% CO-50% PET fabric. In this model, the use of washing and drying machines in the washing process, as well as the cutting and sewing processes, also contributed to carbon emissions. In addition, the environmental impacts of knitted fabric production, which includes the process from raw material to dyed fabric, are important due to the fabric used in physical sample preparation. The production of fibers such as cotton and polyester, which are among the raw materials used in the fabric of the samples evaluated within the scope of this study, has significant environmental impacts. Munasinghe et al. (2021) showed that the impact of cotton fiber on climate change ranges from approximately 0.6 to 9.5 kg CO_2 eq. per kg for conventional cotton. GWP associated with the cotton cultivation and harvesting phase comes from N_2O emissions from fertilizer and pesticide production (57%), application of N_2 fertilizer to land (22%), and agricultural machinery operations (19%) (Baydar et al., 2015). Polyester fibers have higher carbon emissions than cotton fibers due to petrochemical inputs in the production process (Niinimaki et al., 2020; Munasinghe et al., 2016). The energy consumption of spinning machines in the yarn production phase also contributes to GWP (Al Alam et al., 2023). In addition, many studies emphasize that printing and dyeing processes, which require high amounts of steam and electricity, contribute significantly to GWP (Peters et al., 2021; Zhang et al., 2018).

It is clear that fewer carbon emissions will occur in virtual sample preparation processes due to the use of very little fabric and the avoidance of processes that have high environmental impacts, such as dyeing, printing, washing, and embroidery. As expected, in this study, much lower GWP values were determined in all virtual samples than in physical samples. Virtual sample production provides improvements in carbon footprint ranging from 85% to 92% (average 87%), depending on the product type.

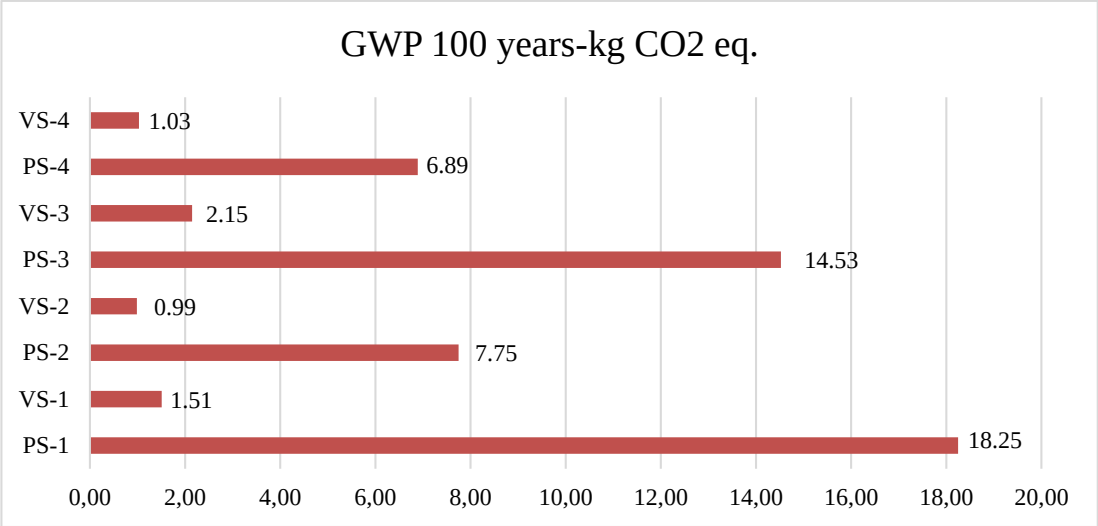


Figure 4.14 Global warming potential (100 years) results

4.3.2 Human Toxicity Potential (HTP inf.)

This impact category reflects the potential effects of toxic substances on human health. The Human Toxicity Potential (HTP) values calculated in this study are presented in Figure 4.15. Among the physical samples, PS-1 exhibited the highest HTP impact (1.175 kg 1,4-dichlorobenzene equivalents [DCB-eq.]), followed by PS-3 (0.968 kg DCB-eq.), PS-2 (0.715 kg DCB-eq.), and PS-4 (0.590 kg DCB-eq.). In contrast, virtual samples (VS-1 to VS-4) demonstrated significantly lower HTP values, ranging from 0.092 to 0.128 kg DCB-eq. These results indicate an approximate 87% reduction in HTP when virtual sample preparation is employed instead of conventional physical methods. This substantial difference underscores the environmental and human health advantages of adopting virtual sampling technologies in the apparel-manufacturing sector.

The integration of virtual sampling enables apparel producers to eliminate many resource-intensive and chemically hazardous processes inherent in physical sample development. This shift not only mitigates environmental toxicity but also enhances occupational health and safety by reducing workers' exposure to harmful substances.

Furthermore, existing literature supports that digital tools in the fashion industry facilitate safer and more streamlined product development processes (Kozlowski et al., 2012).

Previous research has primarily focused on broader production phases, such as fiber cultivation, dyeing, and finishing, as the main contributors to human toxicity (Sandin et al., 2019; Shen et al.,2010). For example, Kazan et al. (2020) identified wet processing during cotton T-shirt production as a major source of HTP due to the use of chemicals such as acrylamide and formaldehyde. However, these studies typically assess toxicity impacts across the entire life cycle of textile products, with limited emphasis on the sample production stage. This study extends the current literature by highlighting sample preparation as a distinct and previously underexplored contributor to HTP within garment production systems.

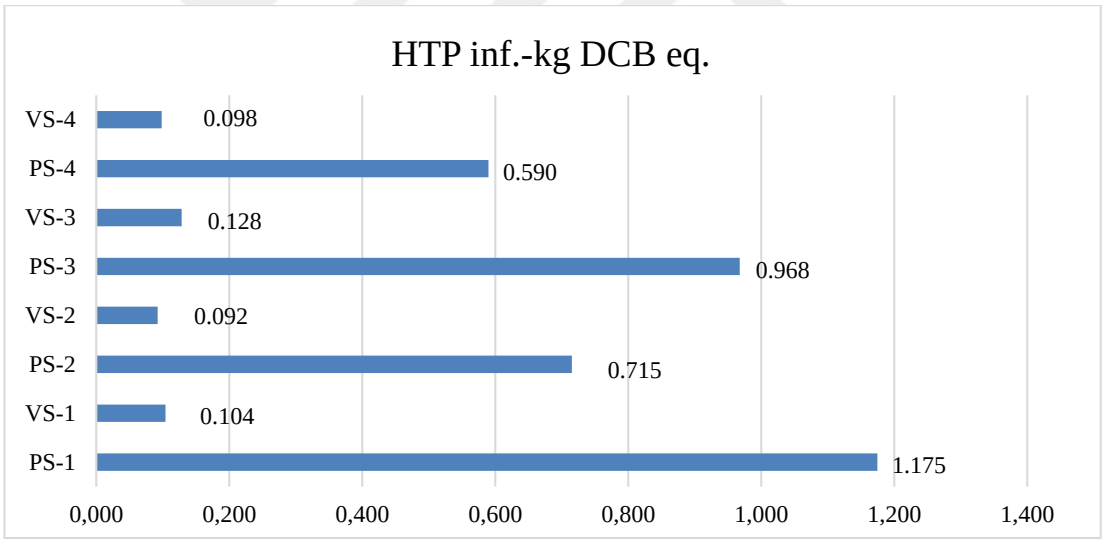


Figure 4.15 Human toxicity potential results

4.3.3 Primary Energy Demand (PED)

In this study, Primary Energy Demand (PED), which encompasses both renewable and non-renewable energy sources, was also assessed (Fidan et al., 2021; Subramanian et al., 2020). The textile industry is one of the more energy-intensive industries (Morita

et al., 2020). In the context of garment sample preparation, the virtual (computer-aided digital) method utilizes only electrical energy, whereas the physical method relies on both electrical and thermal energy inputs.

As illustrated in Figure 4.16, the PED values associated with physical samples were substantially higher than those of virtual samples. Specifically, PS-1 exhibited the highest PED (403 MJ), followed by PS-3 (301 MJ), PS-2 (176 MJ), and PS-4 (162 MJ). In contrast, virtual samples (VS-1 to VS-4) demonstrated significantly lower PED values, ranging from 22 MJ to 45 MJ, corresponding to energy savings of approximately 85% to 94%, depending on the specific sample.

These findings align with the understanding that physical sample development involves several energy-intensive processes, including yarn production, fabric dyeing, and finishing, all of which require substantial amounts of both electrical and thermal energy (Munasinghe et al., 2021; La Rosa and Grammatikos, 2019). In comparison, virtual sample production is entirely digital and relies solely on electricity, primarily consumed by computer-aided design (CAD) systems.

Notably, the PS-3 sample, composed of 100% polyester (PET) fiber, exhibited lower energy consumption compared to PS-1, which consists of a 50% PET and 50% CO blend. However, since energy and steam are used to produce ethylene glycol, xylene, and other sub-processes in the production process of polyester (Subramanian et al., 2020), the amount of energy required for polyester fiber production is more than the amount of energy needed for cotton fiber production (Moazzem et al., 2018). Although less PET is used in PS-1, the reason for more energy consumption is the energy-intensive washing and drying process applied for this sample.

These findings further underscore the feasibility and urgency of adopting virtual sampling systems. The reduction in energy demand associated with virtual sampling supports its alignment with energy-efficient practices promoted by Industry 4.0 and broader corporate sustainability initiatives. Moreover, the results emphasize that digitalization especially when implemented at early stages of the production cycle, such

as sample production can be a strategic intervention to significantly reduce primary energy demand and dependence on carbon-intensive processes.

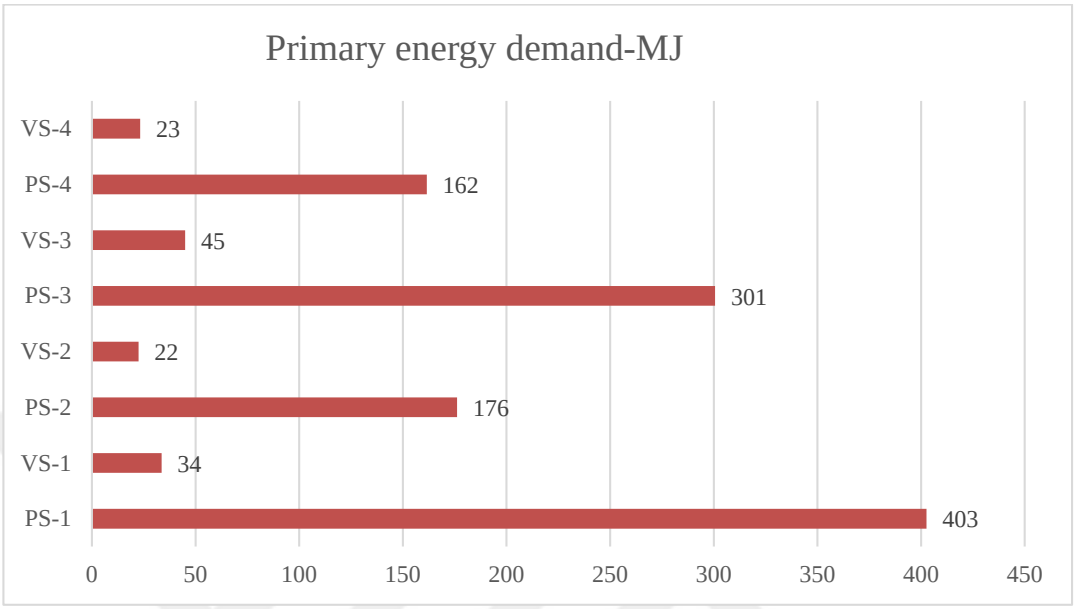


Figure 4.16 Primary energy demand results

4.3.4 Water Scarcity

One measure of human activity's impact on water scarcity in a given region is the "water scarcity footprint" (Chen et al., 2023). To assess the impact of virtual sample preparation on water scarcity, the AWARE impact category method was utilized, as it incorporates region-specific characterization factors for water consumption (Hammar et al., 2023).

When evaluating water consumption for PS-1, which is the only garment sample subjected to washing, it is evident that the fiber production phase accounts for the highest water usage (90%) throughout the entire life cycle (Figure 4.17). As illustrated in Figure 4.18, the highest water scarcity values were observed for the PS-2 (77.04 m^3 world equivalent) and PS-4 (79.44 m^3 world equivalent) models, both of which are composed entirely of cotton. The higher water scarcity impact associated with cotton

garments, compared to other fibers, is primarily due to the significant water consumption during fiber cultivation and production. Among all fibers, cotton requires the greatest volume of water (Moazzem et al., 2021b; Schmutz et al., 2021). Research indicates that cotton fiber production can account for over 88% of the total water scarcity impacts throughout a garment's life cycle (Amicarelli et al., 2022; Peters et al., 2021; Fidan et al., 2021; Sandin et al., 2013). The water used for irrigation in cotton cultivation is a prominent hotspot for garments composed fully or partially of cotton (Sandin et al., 2019). Similarly, in this study, PS-1, which contains a partial amount of cotton, exhibited the third-highest water scarcity impact. In contrast, energy-intensive polyester production is less reliant on water, which accounts for the relatively lower water scarcity scores of PS-1 and PS-3 compared to PS-2 and PS-4.

Virtual sample preparation, which involves solely digital design and visualization, eliminates most of these water-intensive stages. The only water-related burden arises indirectly from electricity consumption within the Turkish grid mix. Across all sample types, transitioning from physical to virtual sampling reduced water scarcity impacts by 86% to 91%.

By incorporating water scarcity as a key metric in comparing digital versus physical samples, this study contributes to theoretical frameworks of eco-innovation and resource efficiency. It reinforces the notion that digital transformation can significantly improve environmental performance (Bocken et al., 2014). Furthermore, companies adopting virtual sampling can substantially reduce their freshwater footprint, a crucial metric in sustainability reporting. This shift is particularly relevant for brands operating in water-scarce regions or those aiming to meet science-based targets for water conservation.

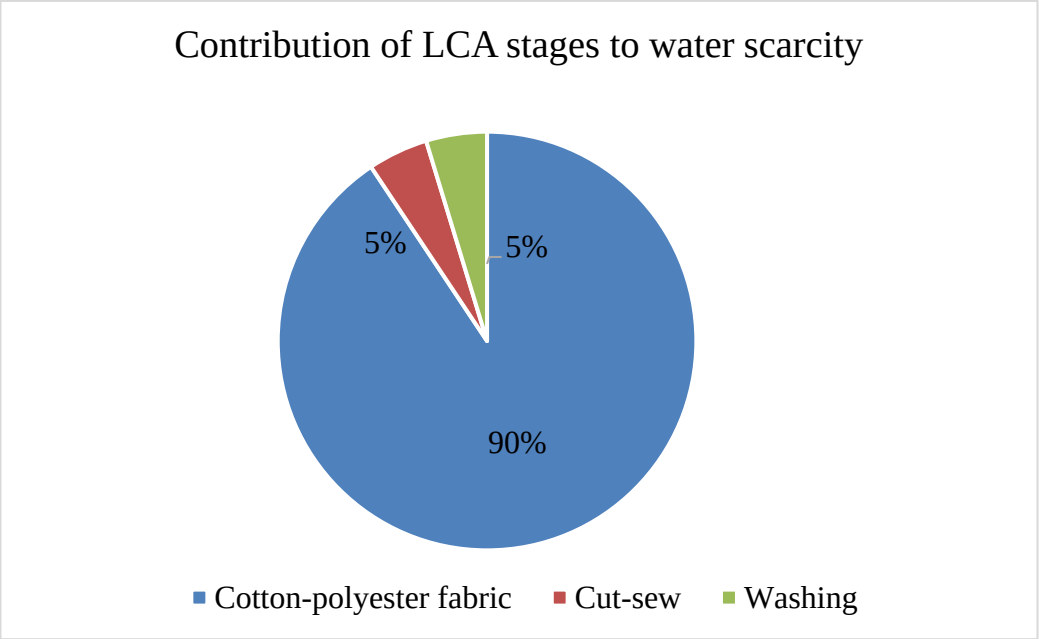


Figure 4.17 Contribution of life cycle phases to water scarcity impacts in PS-1

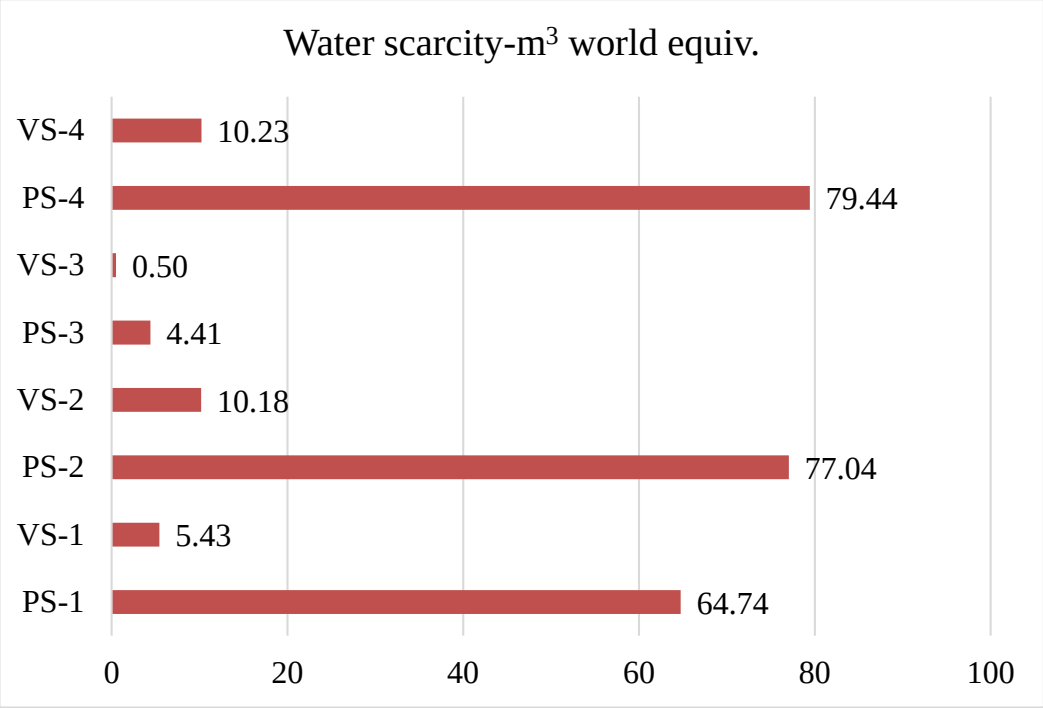


Figure 4.18 Scenario-based comparison of water scarcity impacts

4.4 Scenario 4 – Ozone Washing

This section presents the evaluation of the ozone washing process applied to 100% cotton knitted garments and its comparison with the conventional acid washing method. The analysis focuses on understanding how the replacement of a traditional, chemical-based finishing process with an oxidative technology such as ozone washing influences the overall environmental performance of garment manufacturing.

As the first step of the contribution analysis, the conventional acid washing process was assessed to identify the dominant contributors to its environmental impacts. Figure 4.19 illustrates the contribution of different inputs across the selected impact categories. Electricity consumption was found to be the most influential factor, accounting for over 90% of the total impact in categories such as Acidification Potential (AP), Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity Potential (FAETP), and Photochemical Ozone Creation Potential (POCP). Hydrogen peroxide (H_2O_2) made a notable contribution in the Terrestrial Ecotoxicity Potential (TETP) category, where it represented nearly one-third of the total impact. Thermal energy use, although relatively minor overall, was more visible in the Abiotic Depletion of Fossil resources (ADP fossil) category. Water consumption remained low across all categories, while the contributions of acetic acid and detergent were negligible.

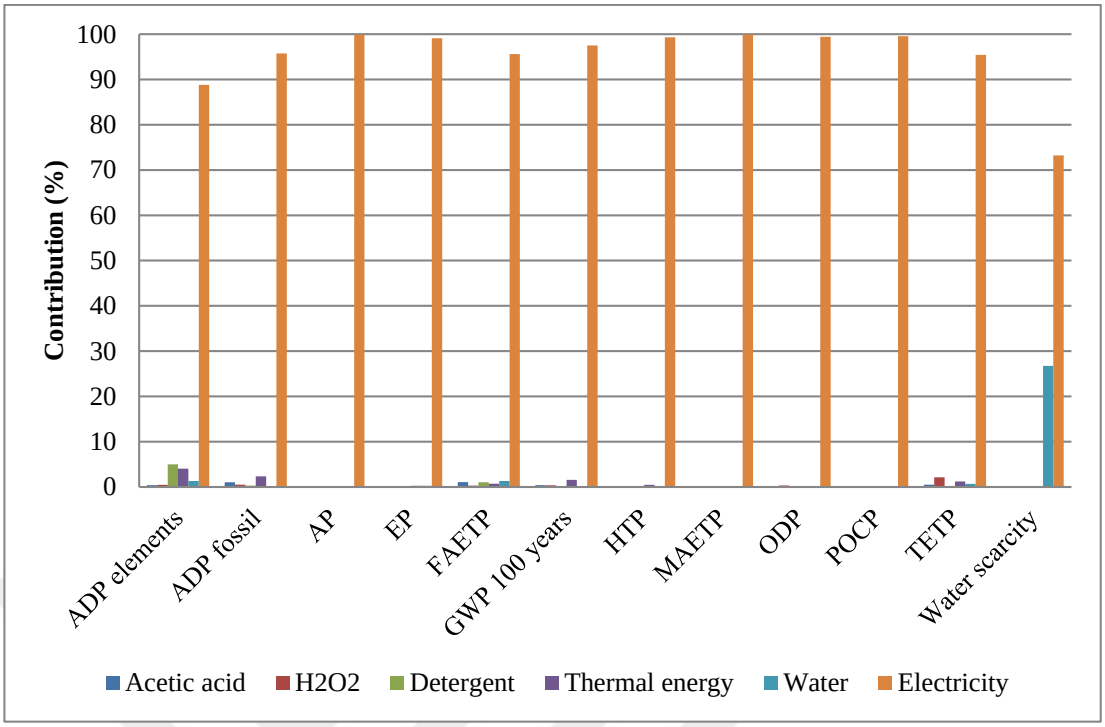


Figure 4.19 Contribution of inputs to environmental impacts in conventional acid washing

Building on these findings for the conventional process, the contribution analysis of the ozone washing process was conducted to examine whether the shift in process design leads to different hotspots. The results are presented in Figure 4.20. Similar to the conventional process, electricity was again identified as the major hotspot, with contributions approaching or exceeding 90% in categories such as Global Warming Potential (GWP), Human Toxicity Potential (HTP), Abiotic Depletion of Fossil resources (ADP fossil), and Marine Aquatic Ecotoxicity Potential (MAETP). In contrast, water consumption became more relevant in the Water Scarcity category, where it accounted for approximately 15% of the total impact. Minor contributions were also observed from the use of softener in Terrestrial Ecotoxicity Potential (TETP) and Freshwater Aquatic Ecotoxicity Potential (FAETP), while detergent use was negligible across all categories.

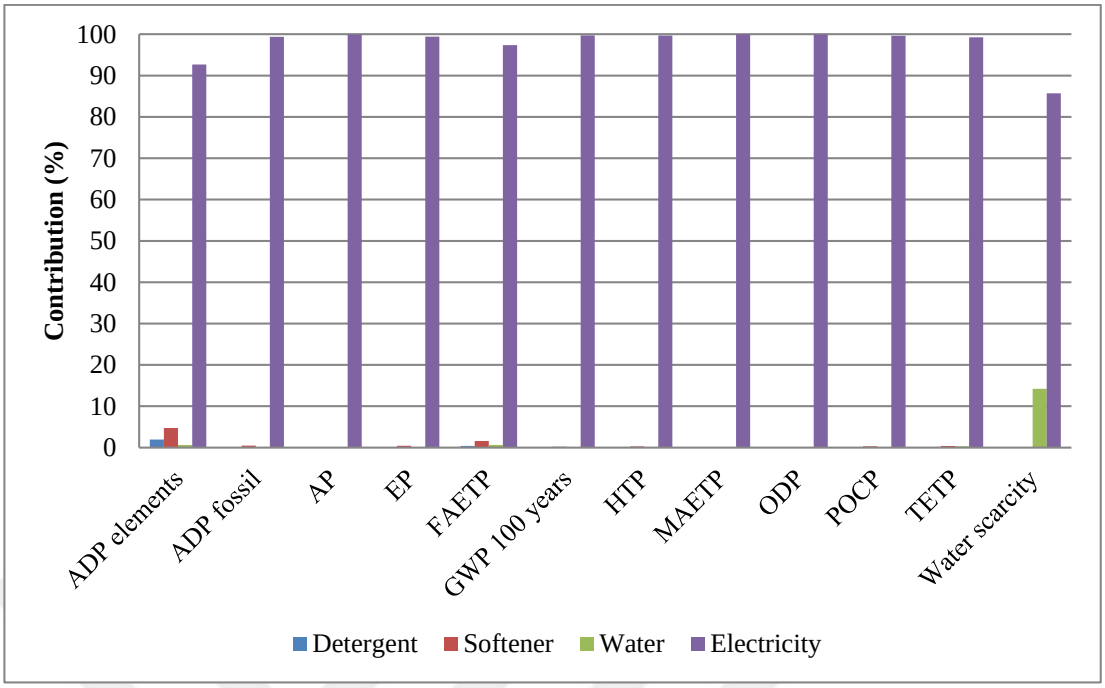


Figure 4.20 Contribution of inputs to environmental impacts in ozone washing

When the two processes are compared in terms of their overall environmental impacts, the results reveal a mixed pattern. As shown in Table 4.3, ozone washing exhibited slightly higher values in most categories, including Abiotic Depletion of Fossil resources (ADP fossil), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Marine Aquatic Ecotoxicity Potential (MAETP), Photochemical Ozone Creation Potential (POCP), and Terrestrial Ecotoxicity Potential (TETP). These increases are mainly attributable to the higher electricity demand of ozone washing (21.4 MJ/kg vs. 20.2 MJ/kg) and the associated upstream burdens of the electricity mix.

On the other hand, ozone washing showed improvements in Water Scarcity, where its impact was lower than that of acid washing (3.63 vs. 4.02 m^3 world equiv.). In addition, minor differences were observed in ADP elements, FAETP, and ODP categories, where the two processes performed almost equally. Importantly, beyond the numerical results, ozone washing also eliminates the use of hazardous chemicals such as potassium permanganate, which represents a critical improvement from a cleaner production perspective.

Table 4.3 Comparison of selected environmental impact categories for acid and ozone washing processes

Environmental Impact Assessment Methods	**Impact categories**	**Unit**	**Acid washing**	**Ozone washing**
CML2001 - Aug. 2016	ADP elements	kg Sb eq.	2.87E-07	2.91E-07
	ADP fossil	MJ	35.58	36.24
	AP	kg SO_2 eq.	0.0432	0.04565
	EP	kg Phosphate eq.	0.001154	0.001215
	FAETP inf.	kg DCB eq.	0.002872	0.00298
	GWP 100 years	kg CO_2 eq.	3.208	3.314
	HTP inf.	kg DCB eq.	4.21E-01	0.443095
	MAETP inf.	kg DCB eq.	2204.72	2329.21
	ODP, steady state	kg R11 eq.	2.30E-11	2.42E-11
	POCP	kg Ethene eq.	0.000174	0.001844
	TETP inf.	kg DCB eq.	0.000482	0.004903
WATER	Water scarcity	m^3 world equiv.	4.0176	3.63

These numerical outcomes (Table 4.3) are further visualized in Figure 4.21, which provides a direct comparison of the two processes across all impact categories on a logarithmic scale. The figure highlights that while ozone washing does not consistently outperform acid washing in every category, it delivers targeted environmental benefits in water-related impacts and chemical substitution, reinforcing its potential as a cleaner production alternative.

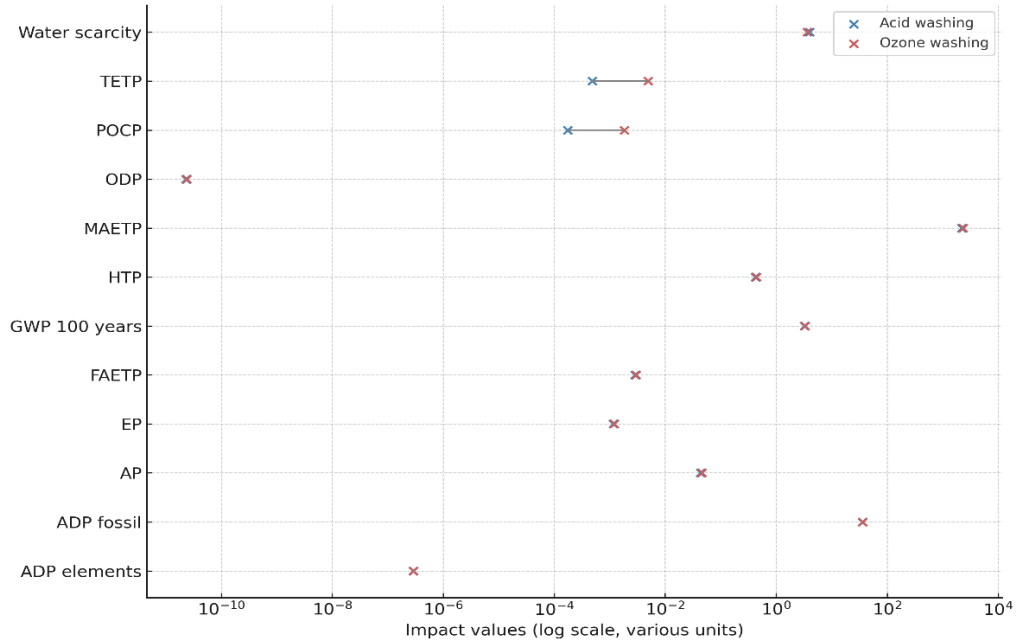


Figure 4.21 Environmental impact comparison between acid and ozone washing processes across CML 2001 categories (log scale)

Another important aspect of this study is that the life cycle inventory for ozone washing was derived from actual field data obtained at pilot scale under real operating conditions. This differentiates the present work from many previous studies, which relied on laboratory-scale experiments or secondary data with limited system boundaries. The integration of real-world operational data, including the electricity required for ozone generation, enabled a more accurate representation of the environmental profile of the process. As a result, the findings of this study provide valuable evidence to the literature by demonstrating that the environmental performance of ozone washing may not always align with the more optimistic results reported in earlier works. Instead, when evaluated under industrially relevant conditions, the electricity-intensive nature of ozone generation substantially shapes the outcomes.

In the broader context of the literature, several studies have reported substantial environmental improvements associated with ozone washing, particularly in impact categories such as fossil resource depletion, climate change potential, and terrestrial ecotoxicity, with reported reductions of up to 76.5% (Sarker et al., 2021; Atav et al.,

2024). These impact categories represent key indicators within life cycle assessment, as they capture critical sustainability dimensions including resource efficiency, greenhouse gas mitigation, and ecosystem health. However, many of these studies applied system boundaries and inventory assumptions that excluded or underestimated the upstream environmental burdens associated with ozone generation. In contrast, the present study explicitly accounts for these upstream contributions, thereby offering a more comprehensive and realistic evaluation of the environmental performance of ozone washing.

From a cleaner production perspective, the results emphasize the critical role of energy efficiency and renewable energy integration in the environmental performance of ozone-based technologies. Although ozone washing eliminates the use of hazardous chemicals such as potassium permanganate and substantially reduces water-related impacts, its dependence on electricity-intensive ozone generation constrains the magnitude of its net environmental benefits under current energy conditions. Consequently, more favorable environmental outcomes may be achieved in future applications when ozone washing is combined with low-carbon electricity mixes and targeted process-level energy optimizations.

Taken together, these findings indicate that, while the improvements observed in this study are more moderate than those reported in parts of the existing literature, the use of field-based operational data provides a more robust and realistic basis for evaluating ozone washing technologies. The results highlight both the opportunities and inherent limitations of ozone washing as a cleaner production alternative and underscore its potential to contribute meaningfully to the sustainability transition of the textile finishing industry when implemented within energy-optimized and low-carbon production frameworks.

4.5 Experimental Results on IL Recovery and Reuse

In the preliminary aqueous two-phase extraction (ATPE) trials, phase separation was achieved only under specific conditions. Clear biphasic systems were observed when 30% aqueous [Bmim]Br solutions were mixed with K_2CO_3 and KH_2PO_4 salts, followed by ultrasonic bath treatment and subsequent cooling in a refrigerator. The photographs of the resulting phase separations are presented in Figures 4.22 and Figure 4.23. Similarly, phase separation was also obtained in the mixture of 30% aqueous [Bmim]Cl solution with K_3PO_4 under the same treatment conditions. The corresponding images of the separation and the recovered IL are shown in Figure 4.24.



Figure 4.22 Phase separation of aqueous solutions of [Bmim]Br and K_2CO_3

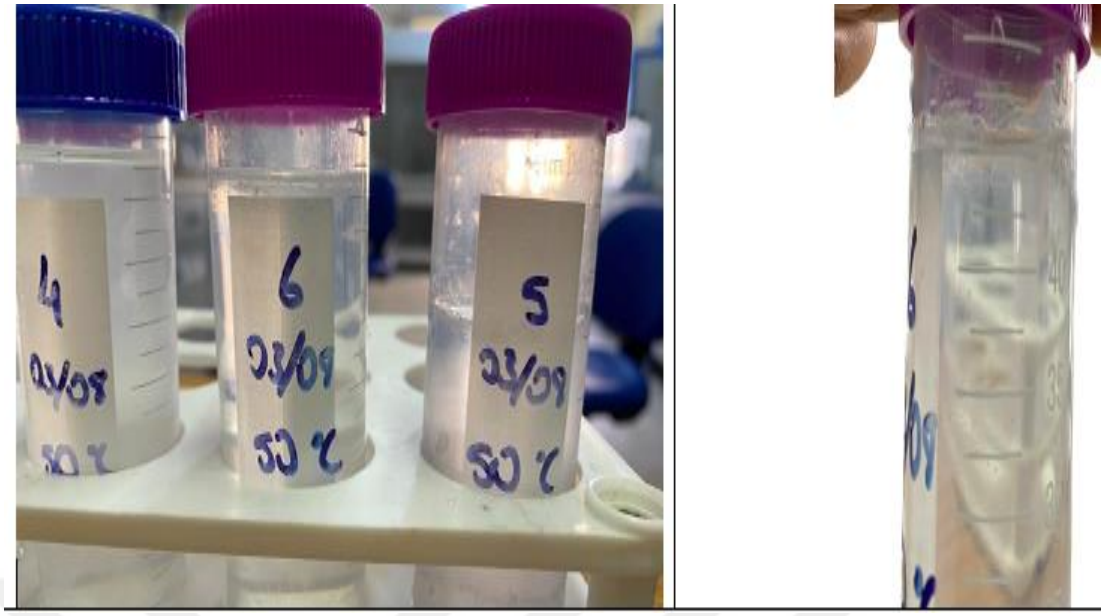


Figure 4.23 Phase separation of aqueous solutions of [Bmim]Br and KH_2PO_4 (Solutions 5 and 6)

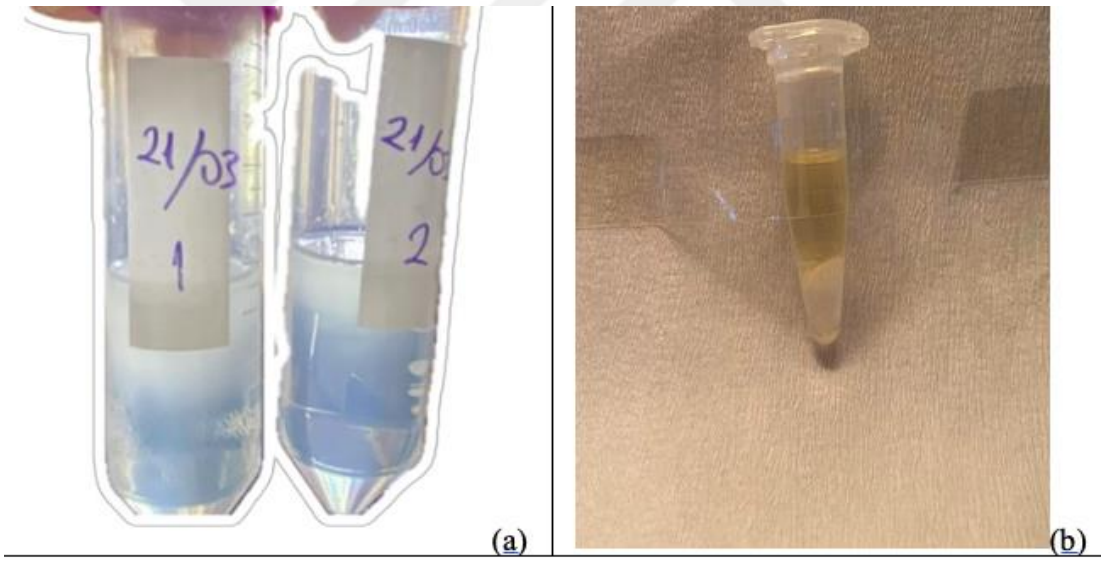


Figure 4.24 Phase separation of aqueous solutions of [Bmim]Cl and K_3PO_4 (a); recovered [Bmim]Cl after ATPE (b)

In successful ATPE experiments, the upper phase was enriched with [Bmim]Br or [Bmim]Cl, while the lower phase contained inorganic salts (K_2CO_3, KH_2PO_4, K_3PO_4). Experimental results demonstrated that increasing IL concentration was the critical factor enabling phase separation, whereas salt concentration had a negligible influence.

Temperature was also found to have no significant effect on phase behavior. Under optimized conditions, up to ~89% recovery efficiency was achieved for the mono-cationic ILs.

To further confirm the presence and chemical stability of the recovered ILs in the enriched upper phases, FTIR analyses were performed. The upper phases of [Bmim]Br + KH_2PO_4 and [Bmim]Cl + K_3PO_4 systems were analyzed and compared with the spectra of pure ILs.

The chemical stability of the recovered ILs was evaluated using FTIR analysis. For [Bmim]Br (Figure 4.25), the characteristic absorption peaks were identified at ~3130 and ~3057 cm^{-1} corresponding to aromatic =C–H stretching vibrations, while the peaks at ~2957 and ~2871 cm^{-1} represented aliphatic symmetric and asymmetric –C–H stretching. Peaks around ~1566 and ~1462 cm^{-1} indicated C=N and C=C stretching vibrations. Additional bands at ~1380–1355 cm^{-1} (–C–H bending), ~1166–1019 cm^{-1} (–C–C stretching), and ~949–750 cm^{-1} (aromatic =C–H out-of-plane bending) confirmed the presence of [Bmim]Br in the recovered phase. The results demonstrated full compatibility between the pure IL and the recovered sample.

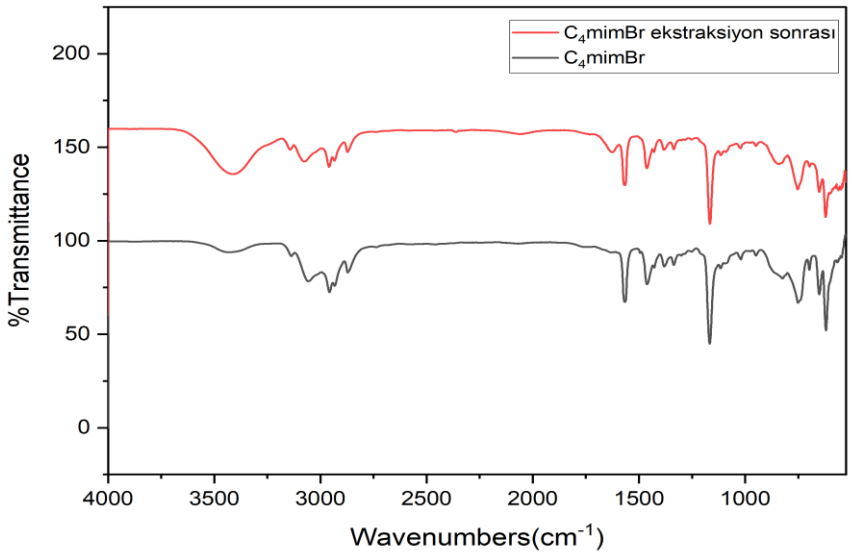


Figure 4.25 FTIR analysis results for [C_4mim]Br

For [C4mim]Cl (Figure 4.26), characteristic peaks were observed at ~3100 cm^{-1} (aromatic =C–H stretching), ~2957 and ~2872 cm^{-1} (aliphatic –C–H stretching), and ~1568–1516 and ~1464–1422 cm^{-1} (C=N and C=C stretching). Additional bands between ~1381–1230 cm^{-1} (–C–H bending), ~1170–1028 cm^{-1} (–C–C stretching), and ~907–736 cm^{-1} (aromatic =C–H bending) were also consistent with imidazolium-based ILs. However, compared to the spectrum of pure [C4mim]Cl, the characteristic aromatic =C–H peaks above 3000 cm^{-1} were absent in the recovered sample. This discrepancy may be attributed to salt interference during the FTIR measurement, which could have masked or overlapped the IL peaks.

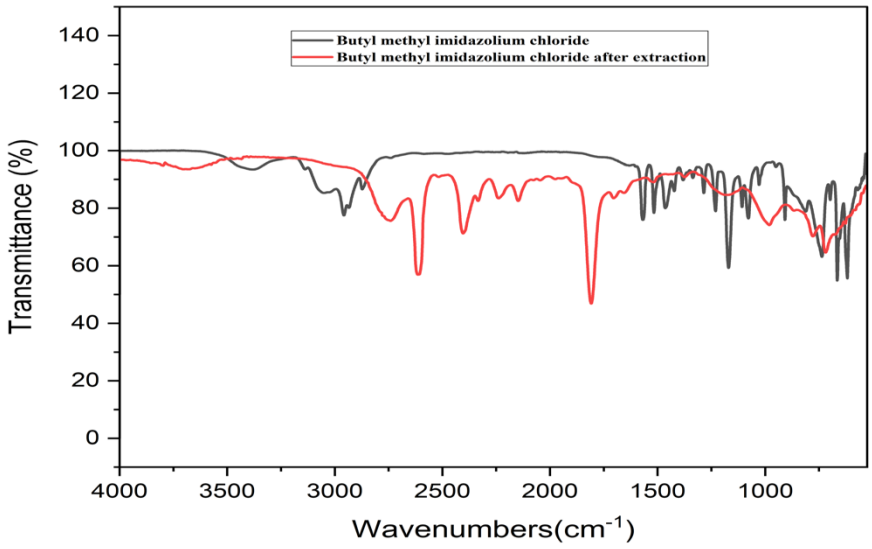


Figure 4.26 FTIR analysis results for [C4mim]Cl

Following these preliminary studies, the ATPE method was applied to real wastewater samples obtained from polyester dyeing trials. In this second experimental set, ionic liquids were successfully recovered from Solutions 4, 6, 7, and 8, as illustrated in Figure 4.27. Although phase separation was less distinct compared to the synthetic solutions, clear biphasic systems were still obtained.

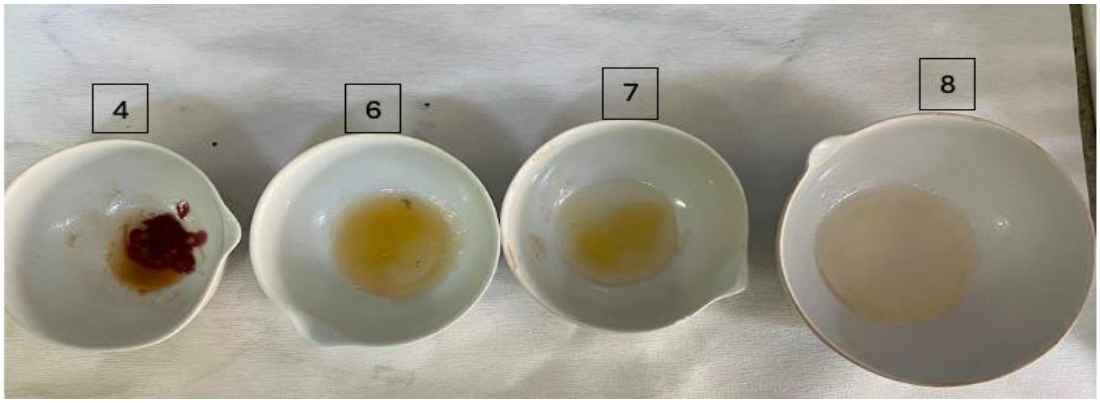


Figure 4.27 Recovered ionic liquids from wastewater (Experimental Set 2)

The FTIR spectra of recovered dicationic ionic liquids were compared with those of pure samples (Figure 4.28). Peaks observed at ~3145 and ~3071 cm^{-1} correspond to aromatic =C–H stretching vibrations, while bands at ~2970 and ~2960 cm^{-1} represent aliphatic symmetric and asymmetric –C–H stretching. Peaks in the range of ~1633–1562 and ~1456–1428 cm^{-1} are attributed to C=N and C=C stretching vibrations. The bands at ~1361–1237 cm^{-1} correspond to –C–H bending, those between ~1167–1023 cm^{-1} to –C–C stretching, and the peaks at ~936–789 cm^{-1} to aromatic =C–H out-of-plane bending. The agreement of all characteristic peaks confirmed that the IL present in the upper phase after extraction was the dicationic bromide ionic liquid, demonstrating successful recovery even from real wastewater.

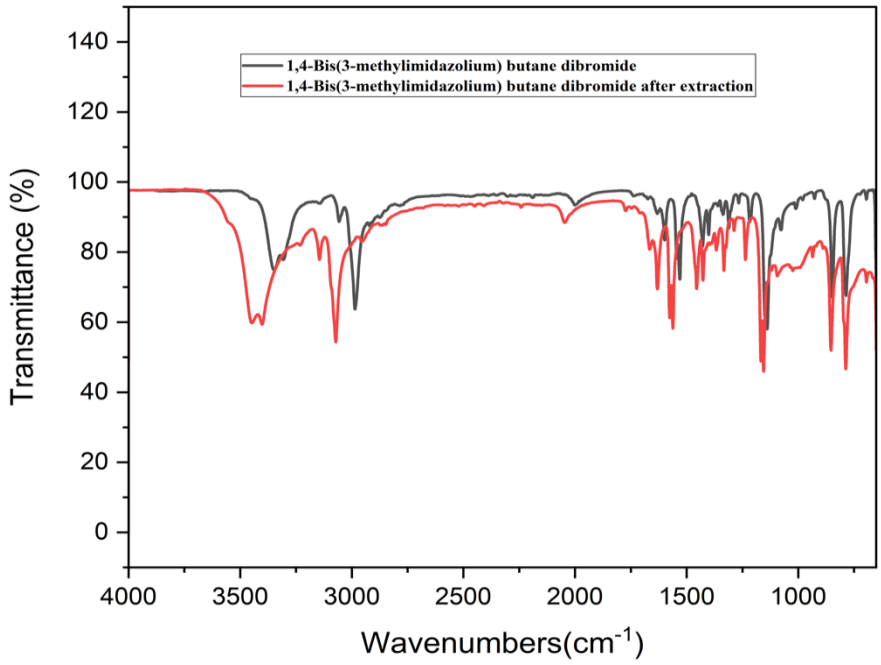


Figure 4.28 Comparison of FTIR spectra of pure and recovered dicationic bromide ionic liquid

Overall, these experiments confirmed the feasibility of recovering ionic liquids from both synthetic solutions and real textile wastewater using ATPE. While recovery efficiencies from real wastewater were slightly lower than those from controlled laboratory solutions due to matrix complexity, the preserved chemical structure and confirmed recyclability indicate the practical potential of IL recovery and reuse in textile applications.

CHAPTER FIVE
CONCLUSIONS

In this study, the environmental impacts of garment production processes were evaluated using the life cycle assessment (LCA) approach, and various cleaner production scenarios were proposed to enhance sustainability performance. The results revealed that electricity and steam consumption were the main contributors to the environmental burdens in the current system. Substituting grid electricity with renewable energy sources yielded remarkable environmental improvements, confirming that energy transition plays a crucial role in achieving sustainable garment manufacturing. The most favorable results were achieved when renewable energy was used throughout all production stages in combination with biodiesel as a transportation fuel, leading to reductions of 74.4%, 84.3%, and 60.9% in global warming potential, acidification, and abiotic depletion, respectively. These findings demonstrate that renewable energy integration substantially enhances environmental performance while reducing dependence on fossil-based resources.

The second cleaner production scenario focused on replacing conventional HT dyeing of polyester fabrics with ionic liquids (ILs). The results indicated that dyeing with ILs can achieve an average reduction of approximately 77% in environmental impacts compared to traditional dyeing, mainly due to lower process temperatures and reduced energy consumption. However, the synthesis of ionic liquids, particularly precursor chemicals such as N-methylimidazole and glyoxal, was found to contribute notably to environmental impacts. Sensitivity analysis revealed that ionic liquid concentration is a key parameter affecting results, emphasizing the need for process optimization. Although IL-based dyeing offers significant potential for cleaner production through energy efficiency and solvent recovery, the environmental benefits depend on proper recovery, reuse, and compliance with green chemistry principles during IL synthesis. Future studies should focus on the development of biodegradable, cost-effective ILs and the optimization of large-scale recovery systems to enhance their industrial applicability.

Another scenario evaluated the environmental and time-related advantages of digitalization through virtual sampling in garment design. The results showed that virtual sample preparation considerably reduced environmental impacts by 85–92% in global warming potential, primary energy demand, and human toxicity potential, and by 87–92% in water scarcity. Although small amounts of fabric are still required for material digitization, the development of comprehensive digital material libraries will likely eliminate this need in the future. Beyond environmental benefits, digitalization enhances efficiency and supports the transition toward sustainable production and consumption models. The integration of virtual sampling into production workflows can thus provide both ecological and operational advantages, particularly when adopted on a larger industrial scale. Nevertheless, digitalization is not entirely free of environmental burdens. The operation of virtual design platforms and digital material libraries requires substantial computational power, which increases electricity demand. Additionally, the processing and storage of large digital datasets rely on data infrastructures that consume water and energy, particularly for cooling systems. Therefore, while digitalization significantly reduces material consumption and transport-related impacts, its indirect resource requirements should also be acknowledged when evaluating overall sustainability.

The final scenario compared conventional acid washing with ozone washing in textile finishing. The analysis demonstrated that electricity consumption dominated nearly all environmental impact categories. Although ozone washing eliminated hazardous chemicals such as potassium permanganate and improved water-related impacts, it did not outperform acid washing overall due to its higher electricity demand caused by ozone generation. The study, which utilized pilot-scale field data rather than theoretical assumptions, provided a realistic assessment indicating that ozone washing cannot yet be considered a universally superior alternative under current energy conditions. However, its targeted benefits in reducing water and chemical use make it a promising cleaner production technology whose performance could be further enhanced by integrating renewable electricity sources and improving energy efficiency.

Overall, the results of all four scenarios clearly demonstrate that achieving sustainability in the textile and garment industry requires a holistic strategy that integrates renewable energy, green chemicals, digitalization, and innovative technologies. Each cleaner production alternative offers unique environmental benefits, and their combined implementation provides the most effective pathway toward reducing the environmental footprint of garment manufacturing and advancing sustainable production in the textile sector.

Taken together, these findings extend the implications of this research beyond the scenario boundaries and point to several industrial and research opportunities. The four scenarios developed in this study present practical and effective cleaner production strategies for improving sustainability in garment manufacturing. However, the findings also show that further research and structural improvements are required to achieve broader progress. One major need is the development of a national textile LCA database that includes region-specific chemical inventories, auxiliary inputs, and energy profiles. Such a database would improve the accuracy of academic assessments and strengthen decision-making in the sector.

The ionic liquid scenario highlights the need to improve IL synthesis routes to enhance environmental performance. The use of bio-based precursors and the scaling-up of recovery and reuse systems could further support industrial applicability. In addition, the comparative evaluation of alternative ionic liquids with different structural properties represents an important future research direction. Renewable energy applications should not remain limited to electricity substitution; using renewable sources to meet thermal energy demand and assessing the feasibility of plant-based hybrid energy systems may reduce the carbon footprint even further. The ozone washing results also underline the need to reduce electricity consumption and integrate renewable energy into ozone generation, while alternative finishing technologies such as laser, plasma, nanobubble, and enzymatic treatments should be tested under real industrial conditions. Furthermore, digitalization can also be extended beyond virtual sampling, and integrated into cutting layout planning, quality control, production scheduling, and logistics to improve operational efficiency and reduce waste.

Achieving industrial transformation will require stronger collaboration among stakeholders. Manufacturers, supply chain actors, academia, and policymakers must work together. Incentives for renewable energy use, transparent data-sharing systems, and the implementation of life-cycle-based sustainability standards will support this transition. Overall, this study demonstrates that a move toward low-carbon, renewable-energy-based, digitalized, and resource-efficient manufacturing models is both achievable and necessary. The findings provide a strong foundation for guiding future research directions and industrial applications in the textile and garment sector.

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