Sustainable Business Model Design for Sportswear: A Life Cycle Assessment Approach Centered on Water Use

Sinem Birsen, Canan Sarıçam, Nazan Okur, Yasin Tek and Ceren Razi

***Abstract*—The textile and apparel sector has a substantial environmental footprint, particularly due to high water consumption throughout various processes. The integration of circular economy practices might have a significant potential in both the manufacturing and retailing of textile and apparel products. Moreover, the assessment of its positive contribution objectively might accelerate the adoption of circular practices. In this respect, a sustainability-oriented business model was developed, grounded in the principles of the cradle-to-cradle (C2C) approach, which aligns with the core values of the circular economy, and its environmental impact was evaluated comparatively with the application of LCA (Life Cycle Analysis) in this study. The proposed business model encompasses the production, distribution, and use phases of T-shirts made from 100% recycled PET, including a collaboration with a sports team, wherein team representatives would be responsible for distributing the products and managing the collection and recycling processes. In accordance with the C2C approach, recovered garments were intended to be reprocessed and reintegrated into the production cycle, as opposed to the cradle-to-grave (C2G) approach, which followed a linear system reliant on 100% virgin PET T-shirts. The environmental performance of the proposed model was conducted by the LCA approach, focusing on the production, transportation, and use phases, and comparing the water use impacts of both C2C and C2G approaches. The results indicated that the model based on 100% recycled PET significantly reduced water usage, demonstrating improved sustainability performance compared to the model developed with the C2G approach. This study makes a distinct contribution to the literature by developing a sustainable business model based on the circular economy and assessing the impact on the environment due to water consumption through LCA, and providing practical insights into water-saving potential for industry stakeholders.**

***Keywords*— Cradle-To-Cradle, Cradle-To-Grave, Life Cycle Assessment (LCA), Water Use.**

I. Introduction

The textile and apparel sector, despite its rapid global growth, is among the most environmentally intensive sectors, with water consumption being one of its most pressing challenges. Wet processing stages, which include pre-treatment (scouring, mercerizing, and desizing), dyeing/printing, washing, and finishing account for approximately 70% of the industry's total water consumption [1], with dyeing and printing alone responsible for about 25% [2]. In addition to high water consumption, the sector contributes significantly to water pollution, as effluents containing dyes, salts, and auxiliary chemicals represent around 30% of total discharged pollutants [3].

These figures highlight the urgent need to protect freshwater resources, which are essential for both ecological integrity and human well-being. However, rising global demand, driven by population growth and unsustainable consumption patterns, continues to intensify pressure on already stressed freshwater systems [4], [5]. In this context, the fast fashion model further amplifies the environmental burden through excessive raw materials use, water consumption, and waste generation. Given the sector's need to shift towards the circular economy, LCA provides a reliable method for evaluating the effects of circular economy practices.

This study aims to design a C2C-based business model for the production, distribution, and use of T-shirts made from 100% Recycled PET. Unlike most existing studies that focus on evaluating current systems across multiple impact categories, this research makes a distinct contribution by developing a sustainable model and assessing the impact on the environment due to water consumption through LCA. The model is also compared to a conventional C2G-based business model based on a 100% Virgin PET T-shirt, providing practical insights into water-saving potential for industry stakeholders.

II. Literature

LCA is a systematic framework for evaluating the environmental aspects and potential impacts of products, processes, or services throughout their entire life cycle. It encompasses all stages, including raw material extraction, manufacturing, transportation, use, and end-of-life management [6]. The methodology is structured into four interrelated phases, which are goal and scope definition, inventory analysis, impact assessment and interpretation. These phases are iterative and interconnected, allowing for refinements as new data becomes available, thereby ensuring the accuracy and relevance of the assessment.

The first phase, goal and scope definition, establishes the foundation of the study by clearly articulating its purpose, the intended audience, and the application of the results. The scope defines the system boundaries, functional unit, and key

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assumptions. System boundaries determine which processes and flows are included in the analysis. A well-defined goal and scope ensure that the assessment is focused and methodologically sound, guiding subsequent phases effectively.

The second phase, life cycle inventory (LCI), involves the collection of quantitative data on all relevant inputs and outputs within the defined system boundaries. Inputs may include raw materials, energy, and water, while outputs typically consist of emissions to air, water, and soil, as well as solid and hazardous waste [7]. This phase generates the data needed to evaluate environmental performance.

The last phase, life cycle impact assessment (LCIA) and interpretation, translates inventory data into meaningful environmental impact indicators. By analyzing the outputs from the inventory phase, such as emissions, resource usage, and waste, LCIA provides insights into potential environmental impacts such as climate change, acidification, human toxicity, and water use. The water use category reflects the impact of water withdrawals on freshwater availability and is typically quantified using the water scarcity footprint, measured in m^3 water equivalents.

By offering a quantitative basis for comparing alternatives, LCA serves as a valuable tool in guiding the transition toward circular economy practices. Moreover, it aligns with broader global sustainability frameworks, including the European Green Deal and the United Nations Sustainable Development Goals (SDGs). As LCA methodology continues to evolve, it plays an increasingly critical role in supporting environmental sustainability and resource efficiency.

III. Method

In this study, the steps outlined in the flow diagram presented in Fig. 1 were followed sequentially to achieve the study's objectives.

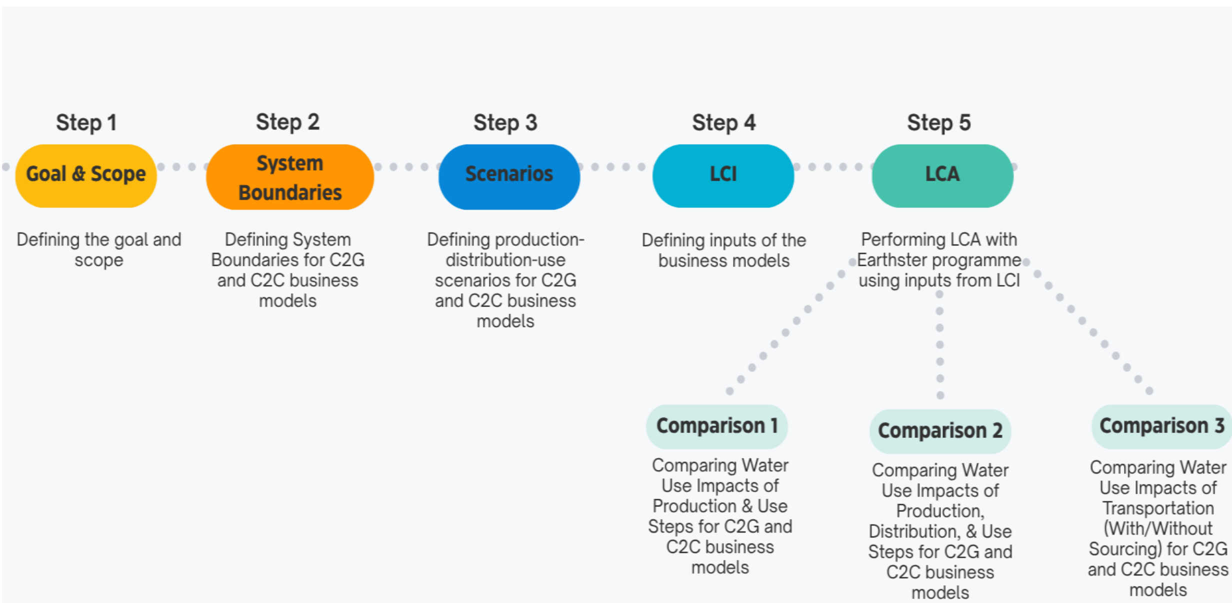

Fig. 1. Steps for designing and analyzing a sustainable business model.

In the first step, the goal and scope of the study were clearly defined. Within the scope of the study, two business models were designed, and it was planned to conduct LCA for two of the business models, which contain two different sports t-shirts, one made from 100% virgin PET fiber and the other from 100% recycled PET fiber. The environmental impacts of both business models, based on C2G and C2C approaches, were evaluated and compared in terms of the water use impact category.

In the second and third steps, the system boundaries and relevant business model scenarios were established for two distinct models. For the 100% virgin PET t-shirt, the system boundaries were defined based on the C2G approach and consisted of 13 main stages: fiber and yarn production, knitting, wet processing (encompassing dyeing and finishing), garment production (including cutting, sublimation printing, sewing, and packaging), distribution, use phase (household laundering and drying), and end-of-life management.

For the recycled PET t-shirt, the system boundaries were defined based on the C2C approach and consisted of 18 stages, beginning with the collection, screening, sorting, and pre-processing of post-consumer waste, followed by fiber recycling, fiber and yarn production, knitting, wet processing (encompassing dyeing and finishing), garment production (including cutting, sublimation printing, sewing, and packaging), distribution, use phase, and end-of-life management. Under this approach, the 100% recycled PET t-shirt followed a circular model in which post-use garments are collected, reprocessed, and reintroduced into the production cycle, eliminating the concept of waste and extending material utility.

Considering the system boundaries, the production, distribution, and use scenarios for the business models, which are based on C2G and C2C approaches, were developed as demonstrated in Fig. 2 and Fig. 3, respectively.

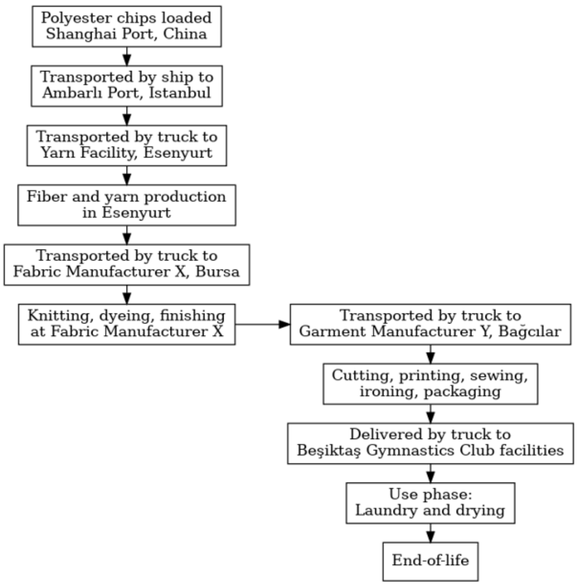

Fig. 2. Scenario for the model developed with the C2G (Virgin PET) approach.

Fig. 3. Scenario for the model developed with the C2C (Recycled PET) approach.

To model the life cycle of the products in a consistent and practicable manner, several assumptions were made concerning material composition, energy consumption, transportation distances, and end-of-life scenarios:

- T-shirts are assumed to be printed.
- Only gelatin is used as a packaging material.
- 20 washes per year with drying at 40°C
- All production activities result in 5% waste.
- All production facilities use 100% renewable energy from on-site solar panels.
- 100% of the textiles are recycled into polyester fibers at end-of-life.
- Transportation of packaging materials is ignored.
- 5% waste is generated at each production stage.
- 2% material loss occurs during fabric recycling in the Liquid State Polycondensation (LSP) machine.
- All polyester waste is converted into polyester chips using the LSP machine, which removes 100% of paint and prints as pre-treatment.

These assumptions were derived from literature sources, industry averages, and standardized databases. They are essential to ensure the feasibility and comparability of the LCA outcomes.

In the fourth step, an LCI was conducted to collect all relevant quantitative data within the defined system boundaries and business model scenarios. Primary data on production processes were collected from SLN Textile facilities, covering the full life cycle of two types of polyester sports T-shirts. Secondary data were obtained from the Ecoinvent v3.10 database, using relevant datasets on electricity consumption, chemical use, and transportation. This step ensured the creation of a comprehensive dataset for subsequent impact assessment. In LCA, the resources consumed at each stage of production are defined as inputs. These inputs include essential elements such as energy, water, chemicals, raw materials, and transportation. The LCI encompasses all input data related to the production, distribution, and use phases of a product.

Data from both primary and secondary sources, gathered during the LCI phase, were processed using the selected LCA tool, the Earthster software, which was employed to perform all calculations for assessing environmental impacts. In line with ISO 14040/44 guidelines—which provide a standardized framework for defining system boundaries, ensuring data quality, conducting impact assessment, and interpreting results to guarantee methodological consistency and credibility—and the EF 3.1 methodology, recommended by the European Commission, which offers a comprehensive set of environmental impact categories and a harmonized approach for evaluating product footprints, the study ensured a robust and transparent assessment process.

In the final step, Water Use impact category was identified as the most relevant impact category to the scope of the study for assessing freshwater consumption within the developed models.

IV. RESULTS

In the following section, the two business models developed with C2G and C2C approaches were compared in terms of their water use impacts. The comparison was performed from three different perspectives:

- Comparing water use impacts of production, distribution, & use steps for business models developed with C2G and C2C approaches
- Comparing water use impacts of production & use steps for business models developed with C2G and C2C approaches

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- Comparing water use impacts of production (with/without sourcing step), and transportation for business models developed with C2G and C2C approaches

In the first comparison, the water use impact was evaluated for production, distribution, and use stages of the life cycle as demonstrated in Fig. 4.

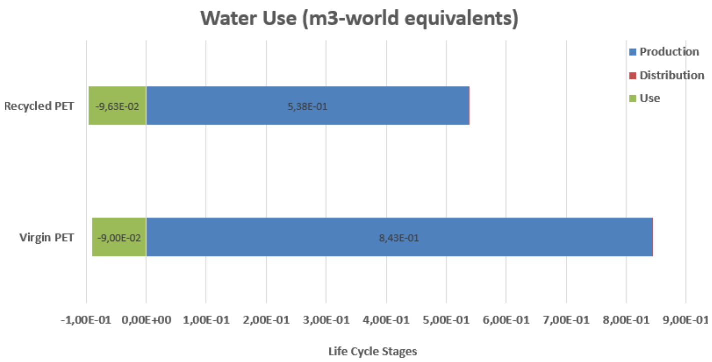

Fig. 4. Water use impact of virgin & recycled PET t-shirts through life cycle stages.

Fig. 4 illustrates the water use potential of the life cycle stages of t-shirts made from 100% virgin and 100% recycled PET. The results indicate that production is the dominant contributor to total water consumption in both business models. However, the virgin PET t-shirt exhibits a significantly higher water use during production (8.43E-01m^3-world equivalents) compared to the recycled PET t-shirt (5.38E-01m^3-world equivalents). This difference can be attributed to the resource-intensive processes associated with virgin PET fiber production, particularly filament spinning, fabric dyeing, and finishing.

In contrast, the use phase shows a negative value for both products, suggesting a positive impact due to the wastewater treatment processes. The positive impact is slightly higher for the recycled PET t-shirt (-9.63E-02m^3-world equivalents) than for the virgin PET t-shirt (-9.00E-02m^3-world equivalents), though the difference is minimal.

The distribution phase is nearly negligible in both cases, indicating that transportation-related water impacts are not significant within the system boundaries considered. In summary, the comparison emphasizes the environmental advantage of 100% recycled PET model in terms of water use, with a notable reduction in production-phase water demand, while use and distribution phases remain comparable between the two business models.

In the second comparison, the production and use stages involved in each business model scenario were examined in detail to identify the steps that contributed most significantly to freshwater consumption. The analysis was based on the life cycle stages specific to t-shirt production. For the sake of clarity and consistency, only the production and use phases, identified by their corresponding stage numbers, were referenced throughout the discussion.

The life cycle of both virgin and recycled PET t-shirts is structured into distinct stages, each represented by a step number. Step 1.1 differs between the two business models: for the 100% virgin PET t-shirt, it involves the sourcing of virgin PET granules, whereas for the recycled PET t-shirt, it refers to the production of recycled PET granules. Similarly, Step 1.2 covers the spinning and texturizing of PET filament fibers, either from virgin or recycled granules. The subsequent stages are common to both systems. Fabric production includes Step 2.1 (knitting), Step 2.2 (fabric dyeing), and Step 2.3 (fabric finishing). Garment production consists of Step 3.1 (cutting), Step 3.2 (sublimation printing), Step 3.3 (sewing), and Step 3.4 (packaging). The use phase is represented by Step 4.1 (household laundry) and Step 4.2 (drying). Finally, Step 5 denotes the end-of-life stage for the virgin PET t-shirt, encompassing disposal, while in the recycled PET system, it refers specifically to the recycled content cut-off point, indicating the boundary of material reuse within the circular process. The environmental impact analysis for each step of 100% virgin and 100% recycled PET t-shirts production was evaluated and presented in Fig. 5.

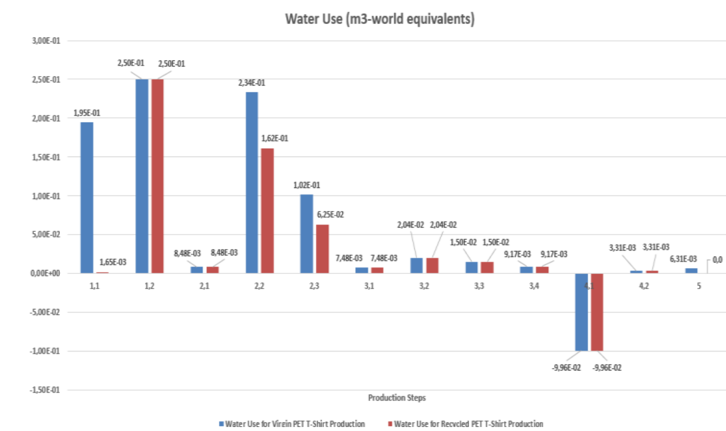

Fig. 5. Water use impact of virgin & recycled PET t-shirts through production steps.

Fig. 5 illustrates the water use impact, measured in cubic meters of world equivalents, for each stage of the life cycle for 100% virgin and recycled PET T-shirts in comparison. The analysis of water consumption across the life cycle stages reveals that Step 1.2 is the most water-intensive process in both models. In the virgin PET scenario, Step 1.2 (PET filament spinning) exhibits the highest water use, primarily due to the intensive nature of fiber processing. Similarly, in the recycled PET system, Step 1.2 (Recycled PET Yarn Production) emerges as the dominant contributor to water consumption. This step is followed by Step 2.2 (Fabric Dyeing) and Step 2.3 (Fabric Finishing) in both models, reflecting the water-intensive characteristics of industrial dyeing and finishing processes in the product’s life cycle. For the 100% virgin PET t-shirt, the lowest water use is recorded in Step 3.1 (Cutting Fabric Panel Pieces), while in the recycled PET model, Step 5 (Recycled Content Cut-Off) demonstrates minimal water use, indicating limited environmental impact in the end-of-life phase. Other steps, including Step 2.1 (Knitting), Step 2.3 (Fabric Finishing), Steps 3.2 to 3.4

(Sublimation Printing, Sewing, and Packaging), and Step 4.2 (Drying), contributed at consistently low levels in both models. The yarn production, dyeing, and finishing stages were the primary drivers of water consumption, whereas cutting, finishing, and end-of-life processes account for relatively negligible impacts.

When the two business models were compared in terms of their similarities and differences, it was found that only Steps 1.1 (Sourcing of virgin PET granules for 100% virgin PET /Production of recycled PET granules for 100% recycled PET), 2.2 (Fabric Dyeing), 2.3 (Fabric Finishing), and 5 (End of Life for 100% virgin PET / Recycled Content Cut-Off for 100% recycled PET) differed, while all other steps were identical for both models. In the steps where differences occurred, the 100% virgin PET model exhibited higher water consumption than the 100% recycled PET business model.

Another comparison between two business models was carried out in order to examine the water use impact in production with and without the sourcing step, and the transportation steps. The water use impacts were demonstrated in Table 1.

TABLE I: TOTAL ENVIRONMENTAL IMPACT FOR THE PRODUCTION AND TRANSPORTATION OF THE T-SHIRTS MADE UP OF VIRGIN PET AND RECYCLED PET

Business Model	Water use (m^3-world equivalent
Total Impact of producing a T-shirt from Virgin PET	8,43E-01
Total Impact of transportation in the production of T-shirts from Virgin PET (Without Sourcing)	1,52E-03
Total Impact of transportation in the production of T-shirts from Virgin PET (With Sourcing)	3,00E-03
Total Impact of the production of T-shirts from Recycled PET	5,38E-01
Total Impact of transportation in the production of T-shirts from Recycled PET	1,64E-03

The results in Table 1 indicate that t-shirts made from virgin PET have a significantly higher water footprint (8.43E-01m^3-world equivalents) compared to those made from recycled PET (5.38E-01m^3-world equivalents). This considerable difference highlights the water-intensive nature of virgin PET processing, particularly during polymerization and fiber formation stages, which are largely avoided in the recycled PET system.

Regarding transportation impacts, the contribution to total water use is relatively minor in both systems. For virgin PET:

• The transportation impact, excluding raw material sourcing, is 1.52E-03m^3-world equivalents.

• While the impact, including sourcing increases to 3.00E-03m^3-world equivalents, indicating that raw material acquisition has a measurable, though still small, effect on freshwater consumption.

In contrast, the transportation impact in the recycled PET system is 1.64E-03m^3-world equivalents, falling between the two virgin PET cases. This suggests that while recycling reduces freshwater consumption in production, transportation logistics, especially if involving multiple collection and processing sites, can still contribute modestly to the total impact. In summary, the findings reinforce that recycled PET offers a substantial environmental advantage in terms of water use during production. Although transportation impacts are present, their magnitude is negligible when compared to production-related water consumption.

The results of all comparisons indicate that the production phase of the life cycle is the dominant contributor to water use in both virgin and recycled PET t-shirt business models. Yarn production (Step 1.2) accounts for the highest water consumption, followed by fabric dyeing (Step 2.2) and finishing (Step 2.3). In contrast, stages such as cutting, packaging, and end-of-life / recycled content cut-off show minimal impact. Key variations in water consumption between the two models are only associated with the wet processing (Steps 2.2 and 2.3), material sourcing (Step 1.1), and end-of-life / recycled content cut-off (Step 5) steps, where the 100% virgin PET model shows higher freshwater consumption in these steps. In addition, the use phase of the life cycle contributes a small negative value due to avoided water burden, while transportation-related impacts remain negligible in both models. In conclusion, 100% recycled PET T-shirt business model, developed with C2C approach, demonstrates a significantly lower water footprint, highlighting its environmental advantage in textile production.

V. CONCLUSION

This study states the importance of addressing the environmental impacts of the textile and apparel sector, particularly in terms of freshwater consumption, a critical issue driven largely by wet processing stages such as dyeing and finishing. The fast fashion model, combined with increasing global demand, increases water stress through excessive resource use and pollutant discharge. In response to these challenges, this research proposed a C2C business model based on the production and reuse of 100% recycled PET t-shirts, offering a circular alternative to conventional C2G production based on virgin PET.

The life cycle assessment results demonstrate that the production of a virgin PET t-shirt resulted in a water use impact of 8.43E-01 m^3-world equivalents, whereas the recycled PET counterpart showed a reduced impact of 5.38E-01 m^3-world equivalents, reflecting a substantial improvement. Specifically, yarn production (Step 1.2) is one of the most water-intensive processes in both models, yet the water footprint is significantly lower in the recycled PET model. Other steps, such as fabric dyeing (Step 2.2) and fabric finishing (Step 2.3), also contributed notably, while cutting, packaging, and end-of-life processes had minimal water-related impacts. In production steps where key variations occurred, the 100% virgin PET model shows higher freshwater consumption.

Transportation-related impacts, while present, were found to be negligible when compared to the production phase in both models. These findings highlight the environmental advantage of circular strategies like the C2C model, particularly in reducing freshwater consumption, a priority in regions where water scarcity is a pressing issue.

The results of this study are influenced by the assumptions and boundaries defined in the LCA model. Notably, the use of 100% recycled PET represents an idealized scenario that exceeds current industry norms, where recycled content typically remains below 40%. It will be considered that using more realistic recycled PET ratios to enhance the accuracy and applicability of the model. This adjustment would provide more credible results aligned with real-world production conditions.

Overall, the study not only offered a comparative analysis of virgin and recycled PET systems but also provided a replicable framework for evaluating water-saving potential in textile life cycle stages. The results are valuable for industry stakeholders aiming to transition toward more sustainable and circular business practices.

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