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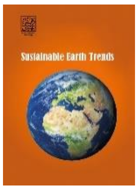

Environmental impact assessment of the paper recycling process using a life cycle assessment (LCA) approach: A case study of Persia Golestan paper factory

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ABSTRACT

This research conducts a Life Cycle Assessment (LCA) of Top White Liner paper produced by Persia Golestan Paper Factory, utilizing SimaPro software and the ReCiPe method to assess its environmental effects. The functional unit for this assessment was 1 ton of Top White Liner paper. Notably, this marks the first application of this method to assess the effects of paper production in Iran. Findings indicate that calcium carbonate is the primary contributor to adverse environmental impacts, including global warming, particulate matter formation, acidification, ecosystem toxicity, and resource depletion. Furthermore, Alkyl Ketene Dimer (AKD) and sodium hypochlorite significantly influence ozone depletion, marine eutrophication, and water consumption. Prioritizing human health and ecosystem quality, the overall environmental score for the product was determined to be -19.8 Pt, signifying a net environmental benefit. A comparative analysis with similar recycled paper products from global SimaPro databases reveals that while Top White Liner demonstrates superior performance in critical categories such as global warming and particulate matter formation, further optimization is required in toxicity, eutrophication, and resource depletion. These findings underscore the imperative of integrating recycled materials and implementing process improvements to mitigate the environmental footprint of paper production. This study exemplifies the utility of integrated LCA methodologies in guiding sustainable production practices and informing policy development within the paper industry, thereby contributing to broader sustainable development goals.

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1. Introduction

The paper industry plays a crucial role in daily life, with diverse applications in packaging, printing and writing, hygiene products, and cardboard box production (Ghasemian and Khalili, 2011). Paper production is closely associated with natural resources such as wood and water. In countries like Iran, it heavily depends on renewable raw materials, which can result in significant environmental issues, including deforestation and pollution from manufacturing processes (Hoseinkhani, 2018). This method uses natural and sustainable resources, thereby reducing the environmental impact of the industry, which is one of the environmental challenges that has received more attention in recent years. One of the primary solutions for reducing the environmental impacts of the paper industry are recycling. This process significantly aids in the conservation of renewable resources and decreases the consumption of energy and water (Pokhrel et al., 2004). Paper recycling, particularly in the production of packaging and printing papers, contributes to the preservation of natural resources and minimizes environmental pollution (Kermanian et al., 2013). Additionally, it lessens the need for tree harvesting, as wood is one of the principal raw materials in paper production. Moreover, using recycled paper consumes considerably less water and energy compared to conventional production processes, which is especially important during periods of resource scarcity (Sharifi Taskouh et al., 2021). Despite these clear benefits, the paper industry continues to face significant challenges in minimizing pollutants and improving production processes. Pollutants such as suspended solids, chemical oxygen demand (COD), and black liquids can severely harm soil and water resources and create substantial waste management issues (Ping et al., 2019). The environmental impacts of the paper industry are typically evaluated using various methods. One of the most modern and widely used approaches for identifying and assessing these impacts is Life Cycle Assessment (LCA) (Ahmadi Saeedabad et al., 2022). The adoption of this method across industries has not only enhanced our understanding of environmental effects but has also supported the sustainable design and management of products and processes. Consequently, LCA is now recognized as an essential tool for achieving sustainable development goals in the contemporary era (Farhadi et al., 2013).

In environmental impact assessments, LCA focuses on identifying and quantifying emissions and environmental effects caused by development processes across different environmental media, such as air, water, and soil. It evaluates the environmental impacts associated with one or more products or processes, examines significant changes in these impacts across the stages of their life cycles, and assesses both the human and ecological consequences of resource consumption and emissions at local, regional, and global levels (Evangelisti et al., 2014). The results of applying the life cycle assessment process in industries can be used in planning and decision-making, gaining public acceptance and stakeholder support (such as society, governments, and organizations), proposing suggested programs, and quantitatively estimating the environmental impact of industrial systems (Widiyanto et al., 2002). The use of life cycle assessment in other industries has also received attention. Ghasempour et al. (2018), in their studies, examined the LCA approach and environmental impact during the production of corn, wheat, and soybean products. The results of this study showed that soybean production, compared to corn and wheat, has the highest energy (fossil fuel) consumption and, consequently, the greatest environmental impact. Ahmadi Saeedabad et al. (2022), in their studies, assessed the environmental impacts of producing SMF and GMF fluting paper using the life cycle assessment method with SimaPro software. The results of their research showed that the production of GMF fluting paper, compared to SMF fluting paper, in the Mazandaran Wood and Paper factory had less environmental impact. Matos et al. (2016), in their studies, evaluated the life cycle of advanced bioethanol production from pulp and paper sludge in a paper mill in Lisbon, Portugal, using the cradle-to-gate life cycle assessment approach. In this study, the life cycle impact assessment was performed using SimaPro software along with the CML-IA impact method, and the assessment method for calculating impacts included global warming (GWP100a), ozone layer depletion (ODP), human toxicity, and freshwater ecotoxicity. The result of this study showed that the use of paper pulp and sludge for bioethanol production simultaneously enables the valorization of this waste and reduces its final amount. Coursely et al. (2018) used the life cycle assessment method to evaluate the environmental sustainability of pulp and paper production. The highest environmental burdens were assessed at a pulp and paper mill complex in northern Finland using SimaPro software and the ReCiPe Midpoint (H) method. The results of this study showed that the pulp production process contributed the main burdens to global warming (46% of total impacts), ozone layer depletion (39%), freshwater eutrophication (55%), human toxicity (46%), metal depletion (42%), and fossil depletion (46%). Overall, the main share of environmental burdens was due to electricity and heat demand, and only to a lesser extent, due to the use of chemicals such as sodium hydroxide and sodium chlorate. Santos et al. (2018), in their study, conducted a comprehensive life cycle assessment considering two different LCIA methods (IMPACT 2002+ and ReCiPe 2008) in the pulp and paper supply chain to identify possible alternatives, using a Portuguese company from the pulp and paper industry as a case study. With this information, improvement suggestions could be provided. This study concluded that three midpoint categories are responsible for 85% of the environmental impacts associated with UWF paper production. For these reasons and to minimize the environmental impacts of the studied supply chain, a shift in electricity sources from non-renewable to renewable energy sources, such as biomass, can be made. In all the above studies, life cycle assessment has been used as an effective analytical tool for identifying and quantifying environmental impacts in various industries. The results of these studies show that production processes in different sectors, from agriculture to the pulp and paper industry, have diverse environmental impacts, mainly dependent on energy consumption, especially fossil fuels, and the use of chemical resources. In most cases, the initial stages of production (cradle-to-gate) have accounted for the majority of these impacts. Also, the use of software such as SimaPro and assessment methods like ReCiPe and IMPACT 2002+ has enabled more accurate and comparable analyses of impacts. Based on the results of these studies, the use of renewable resources, energy efficiency, and waste management have been identified as key solutions in reducing environmental burdens. In this article, the environmental impacts of the Top White Liner paper production process at the Persia Golestan Paper factory are examined to identify possible impacts and provide solutions for their reduction. For this purpose, the ReCiPe method in version 9.0.0.35 of the SimaPro software has been used. This research aims to quantify the various environmental impacts of the production process in this factory and to present appropriate management strategies to reduce environmental damage.

2. Material and methods

2.1. Study area

The Persia Golestan Paper factory is located in Golestan Province, Aq Qala County, along the Aq Qala–Incheh Borun Road, near the Saghar Tappeh area. The factory spans 250,000 square meters and began operations in December 2003. This factory operates as a recycled-material-based industry, utilizing secondary raw materials for its production. It is equipped with two parallel pulp processing lines:

- The white pulp line, which uses a mixture of printed paper waste and white paper trimmings.
- The brown pulp line which processes Old Corrugated Cardboard (OCC) as its main input material.

2.2. Methodology

According to the ISO 14040 standard, the Life Cycle Assessment (LCA) process consists of four main stages, each playing a key role in conducting this analysis accurately and purposefully (Hauschild et al., 2017):

2.2.1. Goal and scope definition

In this stage, the reason for conducting the study (goal) and how it will be conducted (scope of application) are specified. The goal must be clearly defined and aligned with the intended use of the study. A precise and transparent definition of this section ensures that the analysis follows the correct path and that the final results are valid and meaningful. The goal of this study is to analyze and assess the environmental impacts of the Persia Golestan Paper factory based on the life cycle assessment approach within the system boundaries of "gate-to-gate"; this means that all material, energy, and environmental emissions will be assessed from the moment raw materials enter the factory until the final product (Top White Liner paper) is produced. The functional unit is a key concept in LCA studies, allowing for the comparison of different products and services. In the present study, the functional unit is considered to be one ton of the final product. The analysis time frame is set for one year (2023) to ensure data comprehensiveness, as during this period all operational variables — including energy consumption fluctuations, unexpected production line stoppages, seasonal changes, and other unforeseen factors that may be overlooked in shorter periods, such as six months — are properly reflected. This approach enables more precise monitoring of environmental impacts and the identification of critical points in the production process.

2.2.2. Life Cycle Inventory (LCI) analysis

This stage includes the identification, data collection, and quantitative calculations related to all inputs (such as raw materials and energy) and outputs (such as pollutants and waste) throughout the product's life cycle. This stage is considered one of the most critical and sensitive steps in the life cycle assessment process because the quality, accuracy, and timeliness of the data used directly impact the validity and reliability of the final results. The use of outdated, incomplete, or inconsistent data can lead to incorrect conclusions, misleading analyses, and poor decision-making in environmental management. The data were obtained through field studies based on the average performance of the Persia Golestan Paper factory over one year (2023). The nature of this factory is based on recycling, and its raw materials include white wastepaper and brown cardboard; it does not use timber for production. The wastewater from each process is sent to the treatment plant and, after treatment, is returned to the production line. The factory's production waste is also sold. In Fig. 1 inputs and outputs of the top white liner product at Persia Golestan paper factory are shown.

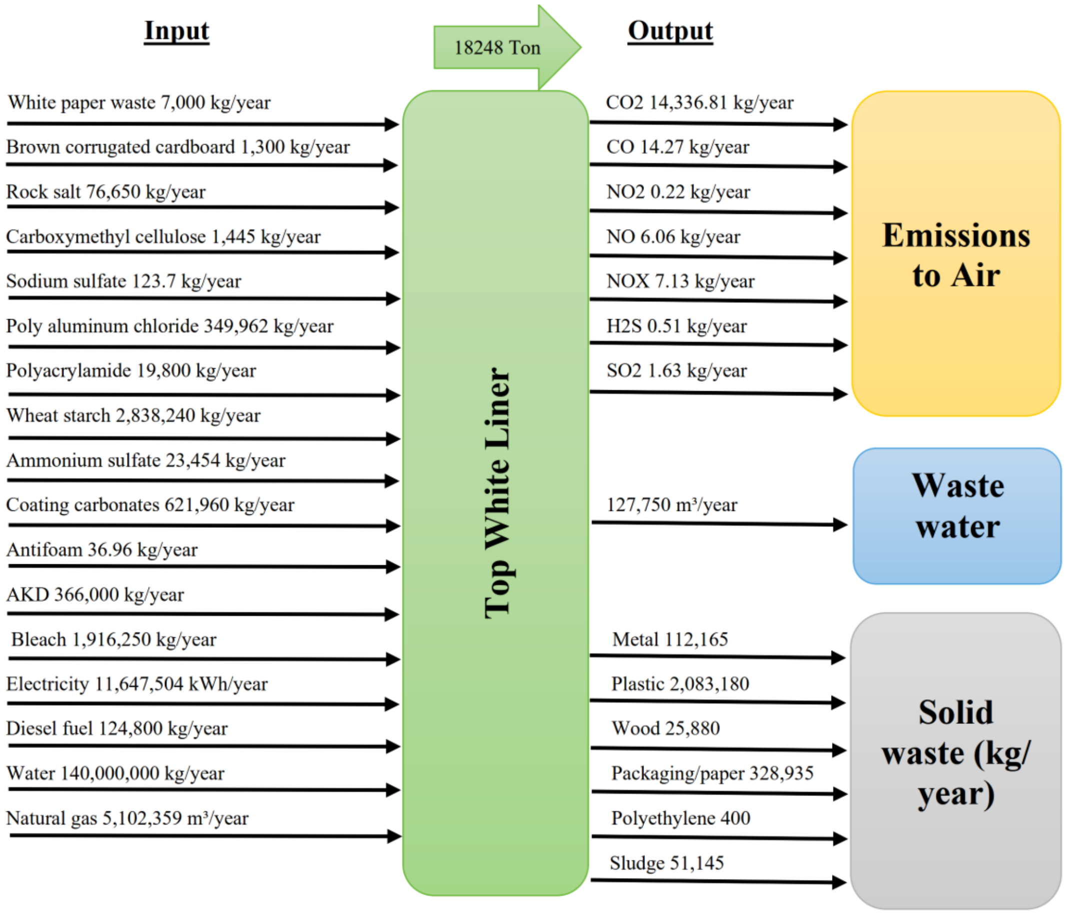

Fig. 1. Inputs and outputs of the top white liner product at Persia Golestan paper factory.

2.2.3. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) of Top White Liner paper production was carried out using SimaPro software version 9.0.0.35, employing the ReCiPe 2016 Hierarchist Endpoint method v1.03 World (2010). This stage of the LCA aimed to evaluate the environmental impacts associated with all inputs and outputs throughout the product's life cycle.ReCiPe is a widely recognized and comprehensive method that converts life cycle inventory (LCI) results into environmental impact categories, supporting both detailed scientific analysis and broader decision-making processes. The LCIA methodology in SimaPro is generally structured into five steps: (1) Characterization, (2) Damage assessment, (3) Normalization, (4) Weighting, and (5) Single score, of which the last four are considered optional according to ISO standards (Database and Support team at PRé Sustainability, 2023). In this study, the characterization and weighting steps were applied to quantify and compare the relative significance of various environmental effects. The LCIA phase offers a comprehensive environmental profile by presenting a spectrum of impact categories, including but not limited to climate change, ozone depletion, water usage, and various forms of toxicity. This phase enables the identification of the life cycle stages that exert the greatest influence on each specific environmental impact (Huijbregts et al., 2017). Environmental impacts were analyzed across 21 midpoint impact categories, including: Global warming – Human health, Global warming – Terrestrial ecosystems, Global warming – Freshwater ecosystems, particulate matter formation, terrestrial acidification, ionizing radiation, freshwater eutrophication, freshwater Eco toxicity, stratospheric ozone depletion, terrestrial Eco toxicity, land use, human carcinogenic toxicity, mineral resource scarcity, human non-carcinogenic toxicity, water consumption – Human health, water consumption – Terrestrial ecosystems, water consumption – Aquatic ecosystems, ozone formation – Human health, ozone formation – Terrestrial ecosystems, fossil resource scarcity, and marine eutrophication. The environmental impacts were further aggregated into three endpoint areas of protection: (i) Human health, (ii) Ecosystem quality, and (iii) Resource availability. This approach enabled a more integrated and comprehensible assessment of the environmental profile of the production process (Database and Support team at PRé Sustainability, 2023). The results provided insight into the phases and operations that contribute most significantly to environmental degradation, thus informing potential strategies for impact reduction.

2.2.4. Interpretation of results

The final stage of the LCA is where the obtained results are analyzed and the main sources of environmental impacts are identified. Additionally, suggestions are provided to reduce these impacts so that better decisions can be made to optimize the process or product. These four stages operate in an integrated manner, and their complete and accurate implementation ensures that life cycle assessment becomes a powerful tool for sustainable decision-making in industrial, environmental, and policy-making domains.

3. Results and discussion

3.1. Characterization of the environmental impacts of the top white liner product at the midpoint level

In the characterization step, the impacts of the environmental interventions identified in the inventory stage were assigned to different impact categories. In this stage, each intervention (whether emission or resource consumption) was quantified based on a coefficient that represents its relative contribution to the creation of a specific environmental impact category and expressed in the conventional unit related to that category. However, due to differences in measurement units among various impact categories, direct numerical comparison between them at this stage is not possible. Therefore, normalization and weighting were conducted in the following stages to enable more accurate comparison and analysis. The results obtained from the characterization stage of the Top White Liner product are presented in Table 1 and Fig 2.

Table. 1. Results of normalization of the Top White Liner product at the intermediate level using the Recipe method.

Effect class	**Unit of measurement**	**Amount**
Global warming\ Human health	DALY	-0.0007
Global warming\ terrestrial ecosystems	Species.yr	$10^{-6}\times 2.33$
Global warming\ freshwater ecosystems	Species.yr	$10^{-11}\times -6.36$
Stratospheric ozone depletion	DALY	$10^{-6}\times -1.02$
Lonizing radiation	DALY	$10^{-7}\times 3.13$
Ozone formation /Human health	DALY	$10^{-7}\times 1.26$
Fine particulate	DALY	-0.00071
Ozone formation, Terrestrial ecosystems	Species.yr	$10^{-7}\times -1.44$
Acidification	Species.yr	$10^{-7}\times -1.17$
Freshwater eutrophication	Species.yr	$10^{-6}\times -1.53$
Marine eutrophication	Species.yr	$10^{-10}\times 4.05$
Terrestrial Eco toxicity	Species.yr	$10^{-8}\times 3.42$
Freshwater Eco toxicity	Species.yr	$10^{-8}\times -1.39$
Marine Eco toxicity	Species.yr	$10^{-9}\times 2.98$
Human carcinogenic toxicity	DALY	0.0001
Human non-carcinogenic toxicity	DALY	0.0001
Land use	Species.yr	$10^{-6}\times 2.33$
Mineral resource scarcity	USD2013	-0.19
Fossil resource scarcity	USD2013	94.1
Water consumption, Human health	DALY	$10^{-5}\times 3.91$
Water consumption, Aquatic health	Species.yr	$10^{-6}\times 2.10$
Water consumption, Aquatics ecosystems	Species.yr	$10^{-11}\times 1.14$

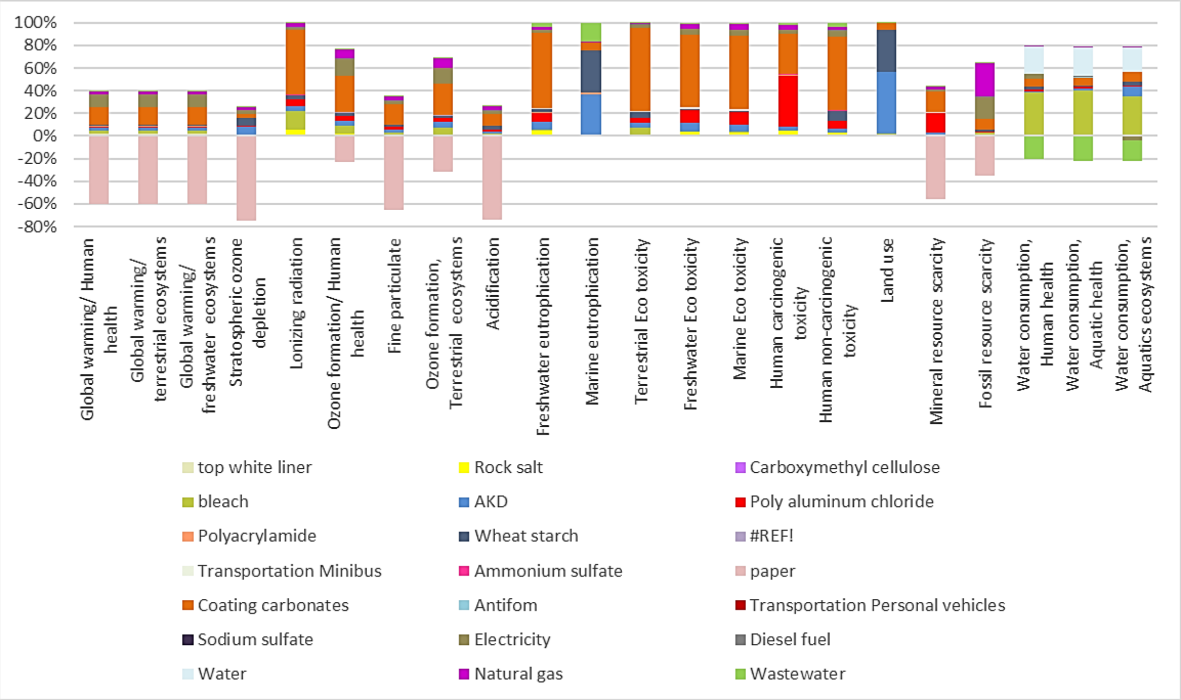

Fig. 2. Results of normalization of the Top White Liner product at the intermediate level using the Recipe method.

As shown in Fig. 1, calcium carbonate used in material preparation is the dominant contributor in numerous impact categories, including global warming (impacts on human health, terrestrial ecosystems, and freshwater ecosystems), ionizing radiation, ozone formation (impact on human health and terrestrial ecosystems), particulate matter formation, acidification, freshwater eutrophication, toxicity (terrestrial, freshwater, and marine ecosystems), non-carcinogenic human toxicity, and mineral resource scarcity. In other categories such as ozone layer depletion, marine eutrophication, and land use, alkyl ketene dimer (AKD) has the highest contribution. Sodium hypochlorite is identified as the main contributor in the water consumption category, due to its wide usage in bleaching and disinfection during the paper production process. Moreover, negative values observed in Fig. 1 indicate environmental savings—meaning that certain impacts are avoided through the use of recycled paper. Specifically, in the Persia Golestan Paper factory, wastewater is treated and reused within the production cycle, significantly reducing freshwater consumption. The factory’s reliance on recycled white shavings and brown cardboard instead of virgin wood fibers further minimizes the use of non-renewable resources, thus enhancing the overall environmental performance of the production system. The recycled raw materials in paper production have approximately sixty percent positive environmental impact in the global warming category, and around seventy percent beneficial effects in the ozone layer depletion and acidification categories. In the categories of mineral resource depletion and ozone formation, they show about thirty percent positive impact. Regarding water consumption, factory wastewater contributes roughly twenty percent positive and environmentally friendly effects, while sodium hypochlorite (bleach) has about forty percent negative impact. Calcium carbonate exhibits nearly eighty percent negative effect in the ecosystem toxicity and eutrophication categories. The negative impact in the diagram indicates the project's environmental friendliness and positive impact on the environment, and cannot be negative on the environment.

The recycled raw materials in paper production have approximately sixty percent positive environmental impact in the global warming category, and around seventy percent beneficial effects in the ozone layer depletion and acidification categories. In the categories of mineral resource depletion and ozone formation, they show about thirty percent positive impact. Regarding water consumption, factory wastewater contributes roughly twenty percent positive and environmentally friendly effects, while sodium hypochlorite (bleach) has about forty percent negative impact. Calcium

carbonate exhibits nearly eighty percent negative effect in the ecosystem toxicity and eutrophication categories.

3.2. Weighting of environmental impacts of white top liner paper at the midpoint level

In this stage, the normalized results for each impact category are multiplied by specific weighting factors. These factors represent the relative importance of each category from the perspective of policy-making, human health, and environmental sustainability. The ultimate goal is to obtain an aggregated score that reflects the overall environmental impact of the studied system.

In the ReCiPe method, weighting is based on two main factors:

- A weighting factor of 400 for midpoint indicators related to human health and ecosystem quality, indicating the high priority of these two domains in the assessment.
- A weighting factor of 200 for midpoint indicators related to resource scarcity, which are considered of somewhat lower—but still significant—importance in the final evaluation.

Overall, the weighting stage, by focusing on the integration of environmental data and converting it into a single, comprehensible indicator, builds a bridge between scientific analysis and practical decision-making. The results for the Top White Liner paper product are presented in Table 2.

Table. 2. Weighted results of white top liner paper at the midpoint level using the ReCiPe method.

Effect class	Unit of measurement	Amount
Global warming\ Human health	Pt	-13
Global warming\ terrestrial ecosystems	Pt	-1.30
Global warming\ freshwater ecosystems	Pt	10^{-5}×-3.55
Stratospheric ozone depletion	Pt	0.01
Lonizing radiation	Pt	0.001
Ozone formation\ Human health	Pt	0.02
Fine particulate	Pt	-12
Ozone formation, Terrestrial ecosystems	Pt	0.08
Acidification	Pt	0.65
Freshwater eutrophication	Pt	0.85
Marine eutrophication	Pt	0.0002
Terrestrial Eco toxicity	Pt	0.19
Freshwater Eco toxicity	Pt	0.008
Marine Eco toxicity	Pt	0.002
Human carcinogenic toxicity	Pt	2.21
Human non-carcinogenic toxicity	Pt	2.36
Land use	Pt	0.88
Mineral resource scarcity	Pt	-0.001
Fossil resource scarcity	Pt	0.67
Water consumption, Human health	Pt	0.65
Water consumption, Aquatic health	Pt	0.12
Water consumption, Aquatics ecosystems	Pt	10^{-6}×-6.35
Total amount	Pt	-19.80

As shown in Table 2, calcium carbonate, used in the material preparation stage, is identified as the main contributor to global warming potential (impacting human health), particulate matter formation, and non-carcinogenic human toxicity. On the other hand, the utilization of recycled materials such as used white paper scraps and brown cardboard instead of raw materials like wood has not only helped to preserve natural forest resources, but has also reduced the carbon footprint of the production process. A significant decrease in indicators such as global warming potential, acidification, fossil energy consumption, and air pollutant emissions all point to the positive environmental sustainability impact of this production model.

3.3. Weighting and final score calculation of the environmental impacts of top white liner paper at the endpoint level

Based on Fig. 3, the highest environmental impacts in the life cycle of Top White Liner paper occur in the Human Health category, followed by Ecosystem Quality. In both categories, the most significant negative impacts are attributed to calcium carbonate used in material preparation, while the eco-friendly effects are primarily associated with the use of recycled paper materials as raw input. In the Table 3 weighted results of top white liner paper at the endpoint level using the ReCiPe method are shown.

Table. 3. Weighted results of top white liner paper at the endpoint level using the ReCiPe method.

Effect class	Unit of measurement	Amount
Total amount	Pt	-19.80
Human health	Pt	-19.80
Ecosystem quality	Pt	0.75
Resources	Pt	0.65

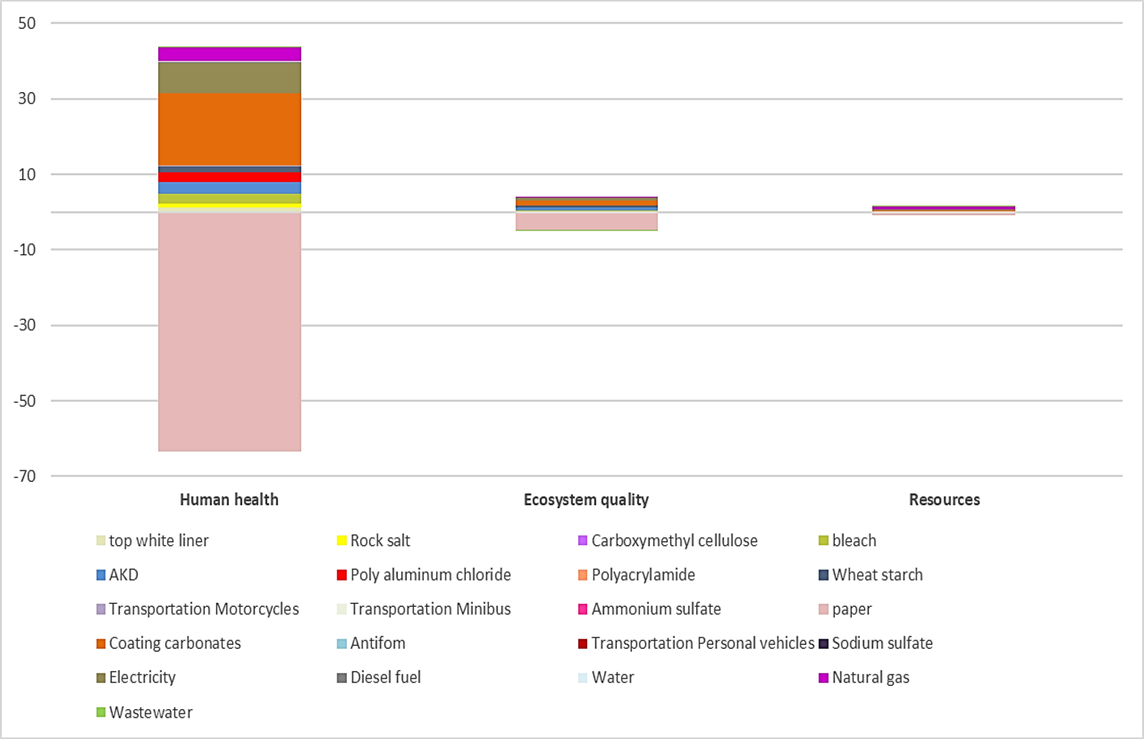

Fig. 3. Endpoint Level Weighting of Persia Golestan Paper Factory Using the ReCiPe Method.

3.4. Comparison of the environmental impact index of top white liner paper with a similar product in the software database

One of the key advantages of Life Cycle Assessment (LCA) is its ability to enable comparisons between different processes for producing the same product, or between two products with similar performance. In recent years, this capability has become a central pillar in the global movement toward "Design for the Environment" and "Process Optimization for Reducing Environmental Impacts." This approach has led to the development of tools that integrate environmental considerations into the design, selection, upgrading, and evaluation of production processes for goods and products. Through this framework, it is possible to comprehensively analyze the environmental impacts of various processes and, based on LCA results, apply corrective actions and optimizations aimed at reducing negative environmental consequences. This systemic approach represents a significant step toward sustainable production and evidence-based scientific decision-making. Considering the LCA conducted for Top White Liner paper and its results, comparing these findings with existing data from developed countries can be highly beneficial in assessing the plant's environmental performance. In Table 4 and Fig. 4, the final environmental scores of the Top White Liner (produced from recycled waste paper) are compared at the midpoint level using the same functional unit. It is worth noting that studies on recycling of waste paper typically consider pulp as the final product, whereas in the process examined in this study, the evaluation goes beyond the pulping stage, with the final output being ready-to-use paper. Therefore, it can be argued that this study extends the evaluation scope by encompassing the entire production chain up to the finished product. The results of this comparison show that the Top White Liner product exhibits the greatest positive and eco-friendly impact in the global warming category (impact on human health), followed by particulate matter formation. In contrast, in the Recycling of Waste Paper studies, the most positive impact appears first in the particulate matter formation category and then in global warming potential. According to the obtained results and the figures and tables presented, the Top White Liner produced by Persia Golestan Paper factory performs worse in some environmental indicators compared to similar cases recorded in global databases. This difference is particularly noticeable in the categories of tropospheric ozone formation, freshwater eutrophication, human carcinogenic and non-carcinogenic toxicity, land use, fossil resource scarcity, and water consumption. However, in two key categories, namely global warming and particulate matter formation, the Top White Liner product demonstrates significantly better performance, showing a marked difference when compared to global reference data in SimaPro software.

Table 4. Comparison of environmental impact categories between top white liner product and a similar product in the software database.

Effect class	Unit of measurement	Recycling of waste paper	Top White Liner
Total amount	Pt	-10.80	-19.80
Global warming\ Human health	Pt	-1.66	-13.01
Global warming\ terrestrial ecosystems	Pt	-0.17	-1.30
Global warming\ freshwater ecosystems	Pt	-4.56×10^{-9}	-3.55×10^{-8}
Stratospheric ozone depletion	Pt	-0.01	-0.01
Lonizing radiation	Pt	0	0.005
Ozone formation\ Human health	Pt	-0.001	0.02
Fine particulate	Pt	-8.48	-11.97
Ozone formation, Terrestrial ecosystems	Pt	-0.01	0.08
Acidification	Pt	-0.33	-0.65
Freshwater eutrophication	Pt	0	0.09
Marine eutrophication	Pt	0	0.0002
Terrestrial Eco toxicity	Pt	0	0.02
Freshwater Eco toxicity	Pt	0	0.008
Marine Eco toxicity	Pt	0	0.002
Human carcinogenic toxicity	Pt	0	22.21
Human non-carcinogenic toxicity	Pt	0	2.35
Land use	Pt	0	0.88
Mineral resource scarcity	Pt	0.0002	-0.001
Fossil resource scarcity	Pt	0.18	0.68
Water consumption, Human health	Pt	0	0.65
Water consumption, Aquatic health	Pt	0	0.12
Water consumption, Aquatics ecosystems	Pt	0	6.35×10^{-10}

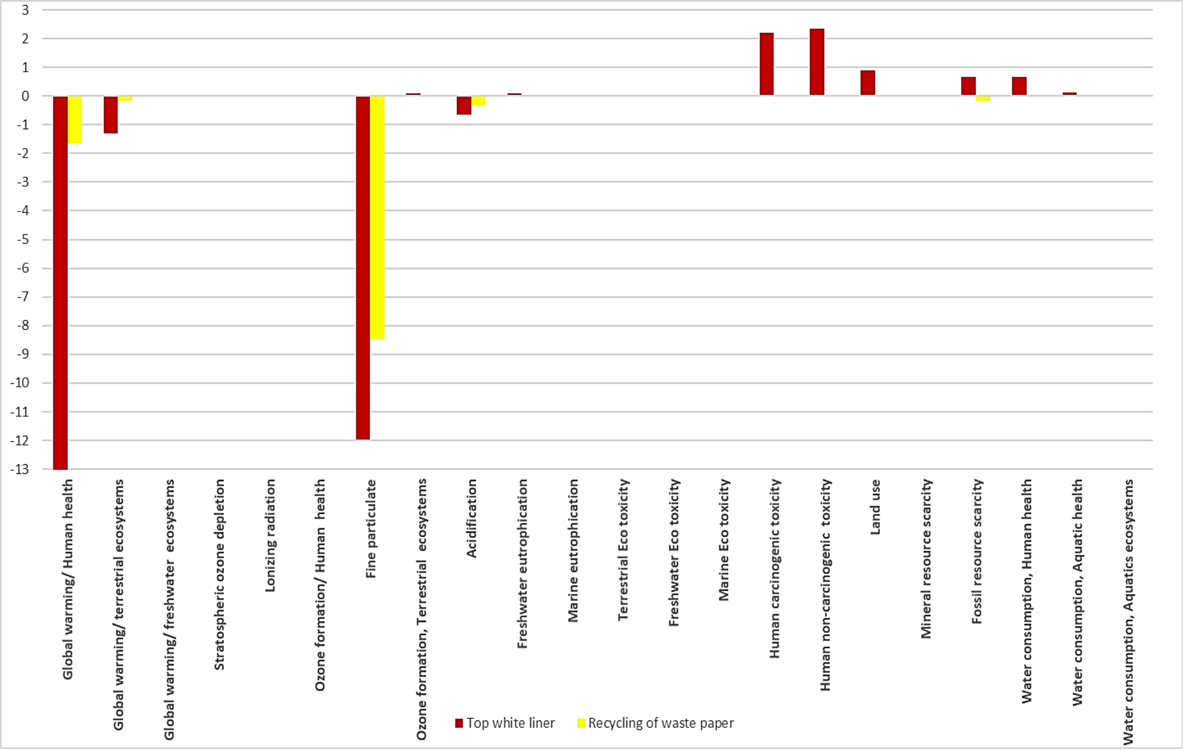

Fig. 4. Comparison of Environmental Impact Categories between Top White Liner Product and a Similar Product in the Software Database.

Table 5 and Fig. 5 present a comparison of the final scores for the Top White Liner product and a comparable product from the global database in SimaPro software. The product used for comparison shows environmentally friendly effects in the Human Health and Ecosystem Quality categories, while it has negative impacts in the Resources category. In contrast, the similar product from the software's database exhibits its most positive effects first in the Human Health category, followed by Ecosystem Quality, and lastly in Resources. Ultimately, the Top White Liner product, with a final score of -19.8, demonstrates greater environmental benefits compared to the recycled waste paper product in the software database, which has a final score of -10.8. It is important to reiterate that most studies related to waste paper recycling only evaluate up to the pulp production stage. However, the process assessed in this study goes beyond pulping and includes the production of final, ready-to-use paper. Therefore, it can be stated that the assessment scope in this study is broader, encompassing the entire production chain - from raw materials to the final product - within the Life Cycle Assessment framework.

Table. 5. Comparison of final environmental score of the top white liner product with a similar product in the software database.

Effect class	Unit of measurement	Top White Liner	Recycling of waste paper
Total amount	Pt	-10.80	-19.80
Human health	Pt	-10.10	-19.80
Ecosystem quality	Pt	-0.51	-0.75
Resources	Pt	-0.17	0.67

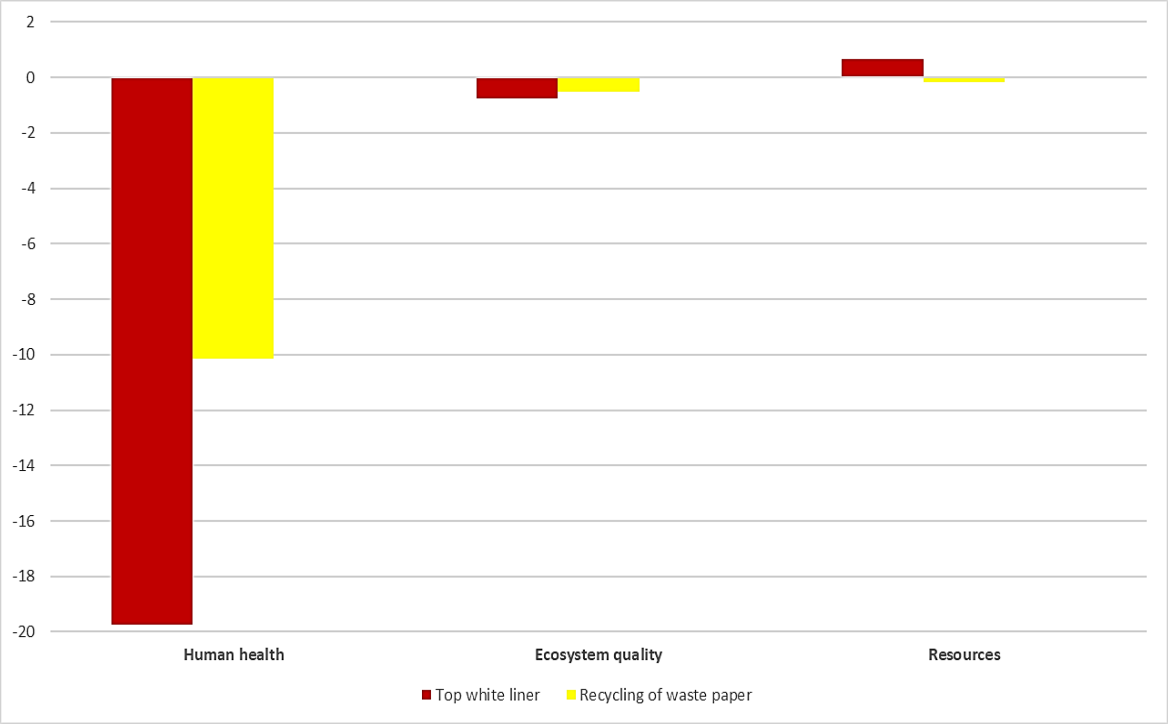

Fig. 5. Comparison of final environmental score of top white liner product with a similar product in the software database.

The analysis of different impact categories based on the ReCiPe method shows that the most significant negative effects are associated with the use of precipitated calcium carbonate and AKD. Although precipitated calcium carbonate itself is a stable and non-toxic material, its extraction, processing, and industrial use (e.g., in paper, plastics, paints, and pharmaceuticals) are typically accompanied by high consumption of fossil energy. This process involves heavy machinery, grinders, and dryers, which lead to the emission of greenhouse gases such as CO_2 and CH_2. Therefore, even outside the cement industry, widespread use of calcium carbonate indirectly contributes to global warming potential because its energy demand is mainly met by non-renewable sources (Doka, 2009). The crushing and transportation of limestone release dust particles (PM_{10} and $PM_{2.5}$). Additionally, the fuels consumed during processing contribute to particulate matter formation (WHO, 2013). The release of heavy metals associated with carbonate extraction (e.g., from certain mineral deposits) may cause soil and water contamination. Oil leaks and chemicals from mining machinery also have environmental impacts (Van der Voet et al., 2005). Dust generated from carbonate processing and transportation can lead to chronic respiratory diseases such as silicosis or occupational asthma. Moreover, exposure to metals associated with the ore is also impactful (ATSDR, 2001). The weighting stage, by applying weighting factors to different impact categories, identified the relative importance of environmental consequences. The results showed that the most significant negative impacts occur in categories related to human health and ecosystem quality, suggesting that these areas should be the main focus for process improvements and environmental impact reduction. Comparison of the environmental indicators of the Top White Liner product with similar samples in global databases reveals favorable performance in key categories such as global warming and particulate matter formation. However, in some other categories like tropospheric ozone formation, freshwater eutrophication, and human toxicity, further optimization is needed. These differences may be due to variations in production technologies, raw materials, or local process conditions. On the other hand, the extensive use of waste paper as raw material and recycling of process water have significantly reduced environmental indicators, especially in categories related to human health and resource depletion. The final environmental impact score of this production system was calculated as -19.8 Pt, indicating its positive effect within the framework of sustainable production. Comparing these results with similar processes such as pure paper recycling showed that by designing a more efficient production system, negative impacts can be substantially reduced. This finding can serve as a basis for developing environmental policies in the paper industry and providing solutions to enhance resource efficiency. In a similar study conducted by Poopak, and Agamuthu 2011 on the life cycle assessment (LCA) of paper production from bagasse (sugarcane residue) at Pars Paper Factory using the CML2 Baseline 2000 method, the results showed that utilizing bagasse and hydropower leads to lower environmental impacts compared to fossil fuels like heavy fuel oil, as both inputs are derived from renewable resources. However, the use of heavy fuel oil had the greatest impact on global warming, which aligns with the findings of the present study. In another study conducted by Dias et al. (2007), the environmental impacts of paper production from eucalyptus pulp in Portugal were examined. The results indicated that the pulp and paper production stages accounted for the highest share of greenhouse gas emissions and energy consumption, which also aligns with the findings of the present study.

4. Conclusion

The results of the life cycle assessment (LCA) of Top White Liner paper indicate that this production unit, by utilizing recycled raw materials and implementing wastewater treatment technologies, has successfully reduced the environmental impacts of the factory and played an effective role in advancing sustainable production. The results of this study emphasize the importance of using recycled materials and optimizing energy and water consumption in the paper industry to reduce negative environmental impacts and achieve sustainable development goals. It is recommended that, based on these findings, corrective actions be taken to reduce greenhouse gas emissions, control volatile organic compound (VOC) releases, and manage water consumption at Persia Golestan Paper factory. Such measures will not only maintain competitive advantages but also contribute to improving the environmental sustainability of the industry. To support these recommendations, the following actions are suggested: transitioning to cleaner or renewable energy sources, enhancing energy efficiency through regular equipment maintenance and upgrades, installing VOC control systems such as activated carbon filters or thermal oxidizers, and adopting water-saving practices including recycling treated wastewater and employing real-time monitoring systems to track and reduce water use.

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