Analysis of the Recovery Process of the Calcine Contained in Damaged Windshields under the Principles of the Circular Economy*

Análisis del proceso de recuperación del calcín contenido en parabrisas dañados bajo los principios de la economía circular

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Abstract:

Objective: This work analyzes the process of recovering calcine by delamination of damaged windshields to separate the glass from a polymeric material called polyvinyl butyral (PVB) at a recycling company based on the principles of the circular economy.
Material and Methods: Three tools focused on the circular economy are used in this study: the material circularity indicator, the circular economy toolkit, and life cycle analysis.
Results and Discussion: By applying the principles of the circular economy, a high linear value was obtained for the calcine recovery and the PVB disposal because byproducts are not currently recycled or reused. Based on the life cycle analysis, the current process for delamination of windshields has several environmental impacts on carbon and water footprint.
Conclusions: Using the principle of industrial symbiosis, the PVB may be reused in other industries so that the circularity index would be enhanced. The environmental impacts on carbon and water footprint could be solved by retrofitting the process and installing a photovoltaic system. In addition, the inversion would be recovered in 3 years.
Circular Economy; Life Cycle Analysis; Material Circularity Indicator; Circular Economy Toolkit
Keywords: Circular Economy, Life Cycle Analysis, Material Circularity Indicator, Circular Economy Toolkit.

Resumen:

Objetivo: este trabajo analiza el proceso de recuperación de calcín mediante la delaminación de parabrisas dañados para separar el vidrio de un material polimérico llamado polivinil butiral (PVB) en una empresa de reciclaje basándose en los principios de la economía circular.
Material y métodos: en este estudio se utilizan tres herramientas enfocadas en la economía circular: el indicador de circularidad del material, el *kit* de herramientas de economía circular y el análisis del ciclo de vida.
Resultados y discusión: al aplicar los principios de la economía circular, se obtuvo un valor lineal alto para la recuperación de calcín y la disposición del PVB porque los subproductos actualmente no se reciclan ni se reutilizan. Con base en el análisis del ciclo de vida, el proceso actual de delaminación de parabrisas tiene varios impactos ambientales en la huella de carbono y agua.
Conclusiones: utilizando el principio de simbiosis industrial, el PVB puede reutilizarse en otras industrias para mejorar el índice de circularidad. Los impactos ambientales en la huella de carbono y agua podrían resolverse modernizando el proceso e instalando un sistema fotovoltaico. Además, la inversión se recuperaría en 3 años.
Palabras clave: economía circular, análisis de ciclo de vida, indicador de la circularidad del material, herramientas de la economía circular.

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Introduction

Today, the world faces anthropogenic environmental changes that present many challenges associated with generating strategies to avoid, reduce, or mitigate current pollution problems [1]. While the use of the planet's resources is increasing at relatively high rates, human activities are becoming less sustainable and must be reduced immediately. Furthermore, owing to new consumer societies and the surprising growth in industrial activity, an increasing number of environmental emissions are being generated, as well as waste and pollutants that cause severe impacts and imbalances on the planet. The Earth's resources are limited; therefore, economic growth and population progress generate an imbalance that the planet cannot support. Hence, it is necessary to search for strategies that allow sustaining the natural balance in the use of resources, which is why controlling waste generation is vital [2].

Searching for a combination of strategies by companies and governments to install a model that allows deep entry into productive sectors, the circular economy (CE) has emerged. Its model is based on reducing wasted resources through the design and implementation of materials, products, and processes that improve their efficiency, incorporating procedures such as recycling, reuse, recovery, etc. In fact, the CE aims to implement sustainability indicators such as water and carbon footprints, among others, to reduce the environmental impacts generated by anthropogenic activities.

Furthermore, the CE aims to be an economic system that replaces the end of life concept by defining its implementation at the micro, meso, or macro levels to achieve its sustainable objectives and generate economic, social, and environmental benefits [2-3].

A CE aims to define a new model of different aspects, which can provide an opportunity to obtain better results for current environmental problems. This model can involve the efficient use of resources through waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection and socioeconomic benefits. The aim is to introduce alternatives to mitigate the socioeconomic and environmental problems that are rising at a level that cannot be stopped [4].

In other words, a CE tends to be an economic model aimed at the efficient use of resources that are trying to be involved in waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials. It is also essential to identify that a CE has a strong relationship with society and the economy because population and economic models support the CE as a new and complete paradigm for solving environmental problems [4-6].

In addition, the CE aims to be a model that reduces the use of virgin raw materials by taking advantage of waste in various production chains, considering the limits of environmental protection and the socioeconomic benefits for the planet. According to the Circularity Gap Report 2020, the world is now only 8.6% circular, meaning that organizations are trying to incorporate solutions and new techniques to make their processes more circular. Among all the minerals, fossil fuels, metals, and biomass that enter the market each year, only 8.6% are recycled. This is a new approach to circular solutions [4-7].

Different principles related to the CE aim to promote minimizing, avoiding, or eliminating waste and pollution because, with these features, productive processes, companies, and the world in general can maximize products and materials and use and regenerate natural systems [8].

In this context, the CE is a paradigm of action that has evolved from a sustainability concept to being applied in the economy, society, and the environment. Accordingly, the CE has become a new methodology that seeks development in various sectors, proposing different strategies throughout the production chain and the use of products and services [9].

The CE has been associated with sustainable development, which considers economic models that respect planetary limits. The CE systemic approach has been used to extend the lifecycle of materials, design out waste, increase resource efficiency, and balance economic growth, environmental protection, and social well-being. Within the United Nations 2030 Agenda framework, CE practices are associated with a significant number of sustainable development goals (SDGs), particularly those that different organizations around the world are aiming to incorporate to improve their systems and redesign new models that can include their ideas with sustainable development [10].

According to previous investigations, some authors have considered the possibility of integrating targets into the CE by areas of application, such as recycling, recovery, efficiency, reduction, and design. Studies in these areas have examined different solutions that can be included in a CE and have led to interesting research that has generated strategies in accordance with the "R" concepts [11-12]. The strategies are related to 3 aspects: the practical application of materials, extending the lifespan of products and their parts, and increasing innovative product manufacturing and use. Each group is presented in distinct subsections where the determination of the different "R" principles is analyzed and defined. Examples of these "R" principles are Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recovery. When a CE is analyzed as a new structure facing environmental problems, these principles or strategies must be considered.

Within the CE landscape, many materials and products can be evaluated in light of this new economic model; the most evident example is glass. Glass has been used in many sectors of industry, and because of its properties, it can also be recycled after use and transformed into various products [3]. In the automotive industry, its main application is in windshields, which are formed from two films of glass (also called calcine) that wrap around a plasticizer known as polyvinyl butyral (PVB) [13-14]. PVB is essentially an expensive plastic used in safe glass laminates, particularly in automobiles, as it prevents, as is the case with windshields, the gradual detachment of the glass from the body by preventing the spread of small pieces of glass in several directions [15-16].

Therefore, this work presents an evaluation of windshield glass recycling (delamination) by interpreting the results obtained from a Life Cycle Analysis (LCA) to determine the environmental loads associated with the recycling process in 2 environmental impact categories, namely, global warming and water scarcity, and to identify areas of opportunity for modification by incorporating the principles of the CE, which aims to improve and reduce the environmental impacts. In addition, circularity indicators such as the Material Circularity Indicator (MCI) are applied to examine the circularity potential of the products' materials with the minimum amount of information available. The Circular Economy Toolkit (CET) allows for areas of opportunity that can be modified to improve the level of circularity of the production cycle to be identified [17]. Finally, modifications in the production process based on the CE principles and strategies are proposed to improve the abovementioned environmental indicators.

Materials and Methods

This project was carried out at a company that recovers calcine from damaged windshields and generates plastic waste (PVB) without further processing. This waste needs to be adequately managed, and the company's solution is to send it to the municipal landfill because it cannot currently be marketed or used again as a plasticizer owing to its characteristics at the end of the recovery process. A development guide for assessing the CE principles is applied to evaluate the current process. The purpose of this assessment is to maximize efficiency in the use of materials and resources, as well as to minimize waste generation, with the final objective being to obtain economically, socially, and environmentally sustainable products and services that allow the problems that arise at the industrial level to be solved, while emphasizing the use of appropriate tools to achieve the CE objectives and managing the considerable consequences generated by constant production [18]. The process of recovering the calcine contained in the damaged windshields was analyzed via LCA, MCI, and CET.

Figure 1 shows the consecutive phases of the process. In Stage 1, the windshields are stacked to be handled and enter the production chain. In Stage 2, the windshields are cut into 3 pieces via steel hammers. Then, they are transported to Stage 4, where the mill separates the glass contained in the windshield from the polymer. In Stage 5, sieving via vibration allows the separation of the calcine from the plasticizer, and once separated, the materials are stored in Stage 6.

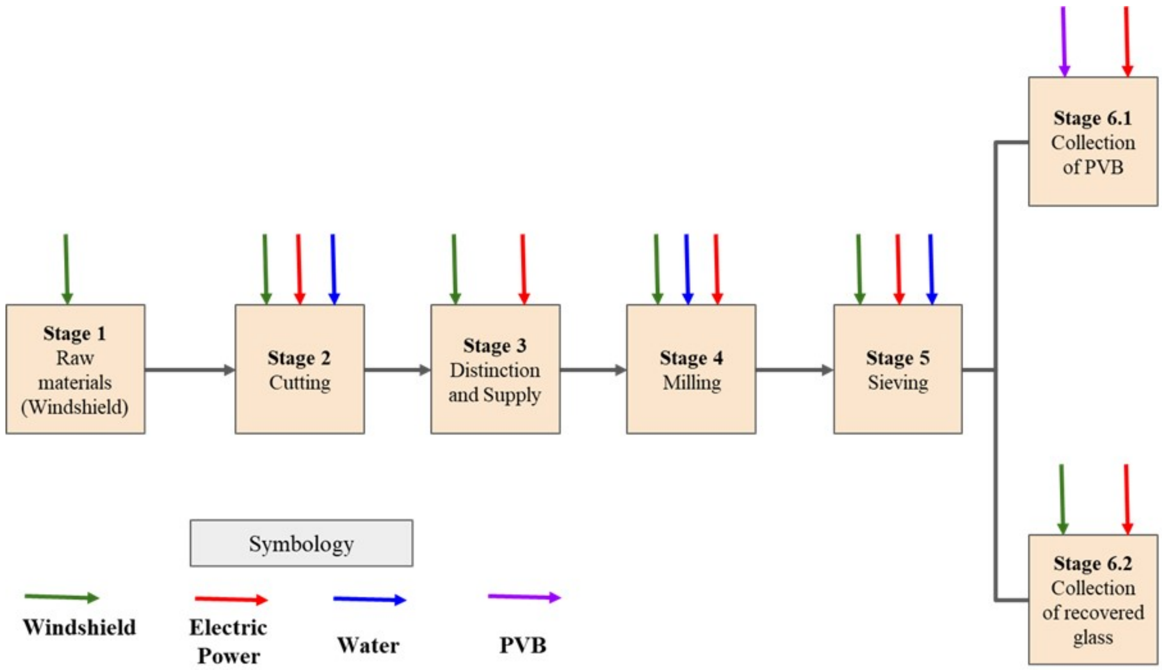

FIGURE 1

Windshield Delamination Process of the Recycling Company

Source: Own elaboration.

It has been estimated from the information provided that in an 8 h working day, 6,300 kg of calcine is recovered from 8,000 kg of damaged windshield, and 1,700 kg of PVB is obtained with glass fragments incorporated into the material. Therefore, the functional unit is 6,300 kg of recovered material.

Life Cycle Analysis

A LCA attributes to products all of the environmental effects from the consumption of raw materials and energy required for their manufacture, the emissions and waste generated in the production process, and the ecological effects from the end of the product's life when it is consumed or can no longer be used. Therefore, this methodology starts from the acquisition of resources to the end of the product's life, considering the main processes in its production [19]. The methodology is based on UNE-EN ISO 14040:2006 "Environmental Management. Life Cycle Analysis. Principles and reference framework. AENOR" and UNE-EN ISO 14044:2006 "Environmental Management. Life Cycle Assessment. Requirements and guidelines. AENOR".

The SimaPro software was used to evaluate the LCA, focusing on the global warming (GW) and water scarcity (WS) categories. These categories were selected because electrical energy (GW) and water are used to avoid dust emissions during the milling stage (WS). The system was delimited by taking into account phase 1 (the supply of raw material represented by the windshields) to the last phase (obtaining calcine and PVB) over an 8 h working day. The LCA allowed for the identification of areas that could be improved according to the CE principles. Furthermore, the fuel consumption used to transport the raw materials was excluded from the analysis.

Material Circularity Index

The MCI was used to assess the circularity index of the materials involved in the calcine recovery process. The MCI was determined according to the instrument developed by the Ellen MacArthur Foundation, which is based on the Excel program, and the value ranges from 0 (highly linear) to 1 (highly circular). Calculating the MCI involves analyzing the flow of primary and recycled materials, the recyclability at the end of the product's useful life, and its durability. In addition, the environmental impact of transportation and energy consumption is considered. This index promotes sustainable design by prioritizing recycled materials, material reuse, and reduced waste generation. Implementing the MCI helps companies close the life cycle of their products, promoting a CE and reducing dependence on virgin resources.

Circular Economy Toolkit

The toolkit evaluates areas according to 2 concepts: company type and product type. First, different types of companies are selected according to the process they perform. In the second aspect, the name of the service or process to be analyzed is entered. It is subsequently necessary to answer 33 questions focused on the characteristics of the process, which are based on 7 subareas:

1. Design, manufacturing and distribution
2. Use
3. Repair and maintenance
4. Reuse and distribution
5. Remanufacturing and refurbishment
6. Product as a service
7. Recycling

Additionally, three fields are taken into consideration:

1. Reduction of the materials
2. Optimization of the materials
3. Industrial symbiosis

Each question must be answered according to the information obtained from the production process to be evaluated.

The type of answers varies according to the subarea, allowing conclusions to be drawn that will provide a schematic diagram of the improvement potential of the corresponding areas. The questionnaire is answered online, as presented in Figure 2 [20]. The toolkit classifies areas for improvement by establishing a color-coded analysis framework, which is defined as follows:

- Green represents a high potential for improvement.
- Yellow represents a medium potential for improvement.
- Gray represents a low potential for improvement.

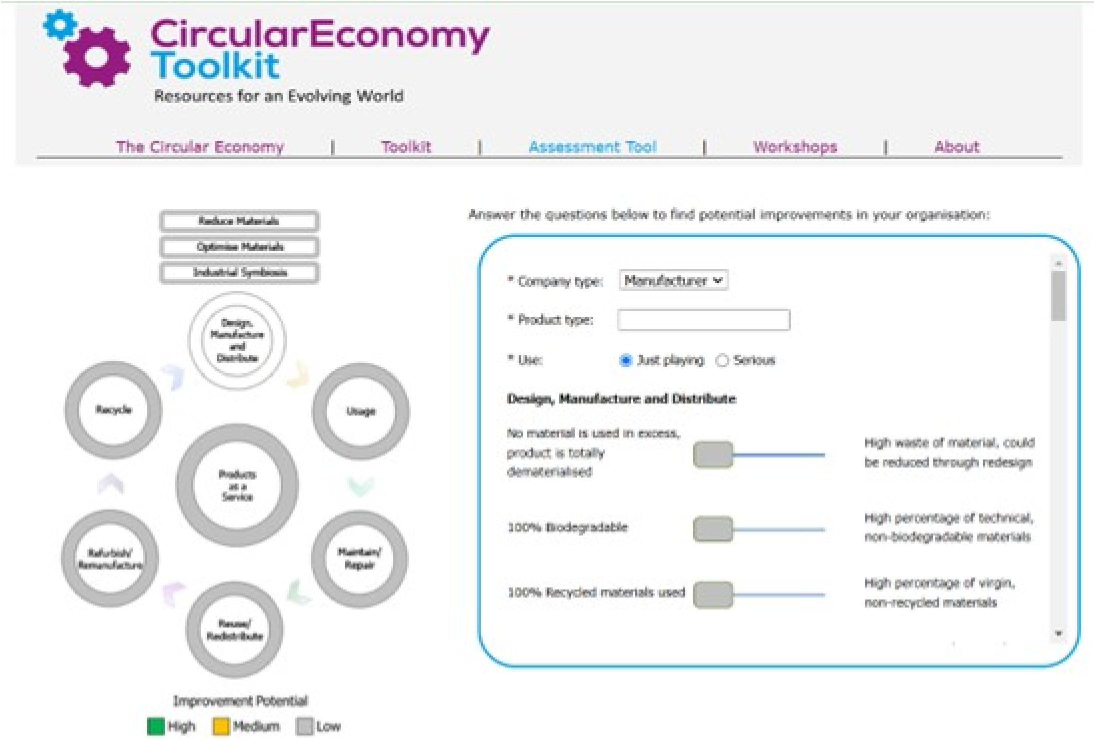

FIGURE 2
Online Circular Economy Toolkit
Source: Taken from [20].

Results and Discussion

The LCA, which uses the SIMAPRO tool with the information in Table 1, revealed a carbon footprint of 33 kg of CO2, as indicated by the GW metric. A comparative analysis revealed that the windshield milling and cutting stages presented the phases with the highest GW values because of their increased use of electrical energy.

TABLE 1
Resources and Materials Necessary for the Windshield Delamination Process.

Stage	Energy (kWh)	Water (L)	Windshield (kg)	PVB (kg)
Raw materials (windshield)	None	**None**	8000	None
Cutting	12.976	144	8000	None
Distinction and supply	6.424	None	8000	None
Milling	25.308	96	8000	None
Supply band	6	None	8000	None
Sieving	3.696	48	8000	None
Collection of PVB	2.798	None	None	1700
Collection of recovered glass	4.488	None	6300	None

Note: kWh = kilowatt-hour, L = liter, kg = kilogram.
Source: Own elaboration.

The second category (water scarcity) involved significant water consumption in 3 stages (milling, cutting, and sieving). The water used in the windshield-cutting stage is the most relevant, as it involves 144 L. In total, 288 L of water is involved in processing the 8,000 kg of windshield.

Material Circularity Indicator

The MCI was estimated via two different simulations. The first one, focused on the calcine, is shown in Figure 3. The MCI was 0.13, which indicates high linearity; therefore, the material has little circularity in the process. This is because the consecutive stages are designed to allow only the glass to be separated from the plasticizer that is adhered to the windshield. In addition, other reasons cause the low value of circularity. The first is reflected in the "reuse" percentages, which are 0% because the process's products and byproducts are not reused in further applications within the company. Second, the recycling rate is 0% because all the raw material is from virgin materials. The percentage of recycling after use (not accounting for the circularity of the studied process) is 95% because the recovery of calcine fluctuates in this percentage due to the superior efficiency of the process of separating it from the polymer and the fact that the amount of glass that is not unglued from the plasticizer is minimal. The material lifetime is included in the simulation. This is represented by the 8 daily working hours of the company and the incorporation of the functional unit, which is defined by the amount of glass obtained versus the amount that is processed, i.e., 6,300 kg obtained versus 8,000 kg processed.

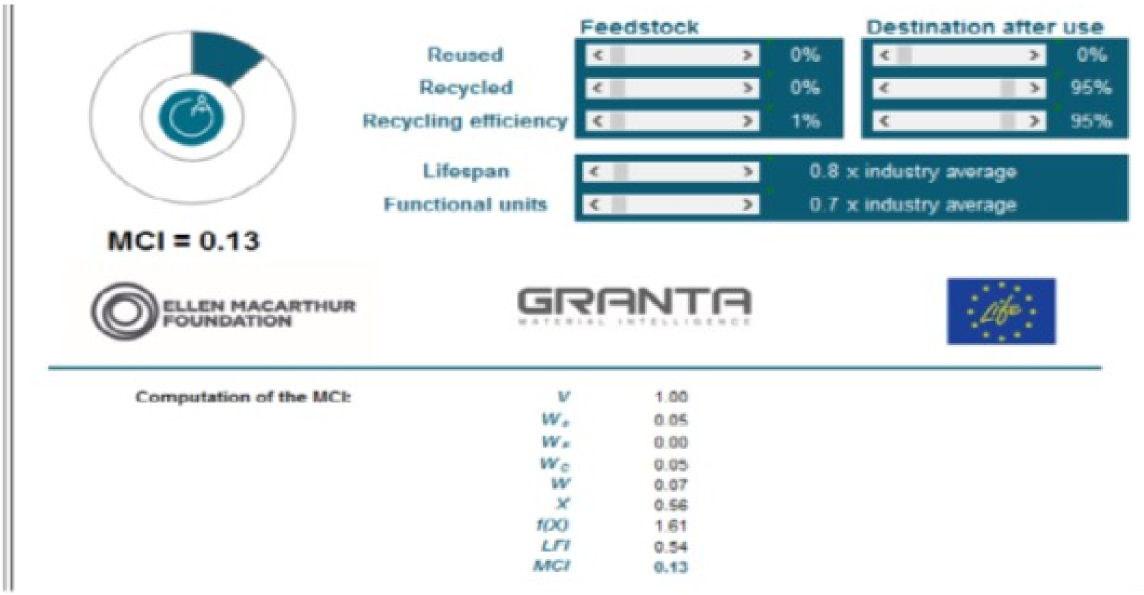

FIGURE 3
Calculation of MCI for calcine
Source: Own elaboration.

The second simulation is represented by the PVB disposal and is shown in Figure 4. It has a value of 0, indicating high linearity, which translates into nonexistent circularity. The main reason is that the raw materials do not come from reused materials, and after their separation, no reuse strategy is applied. In fact, the company simply disposes of them in a landfill, which is not the best solution.

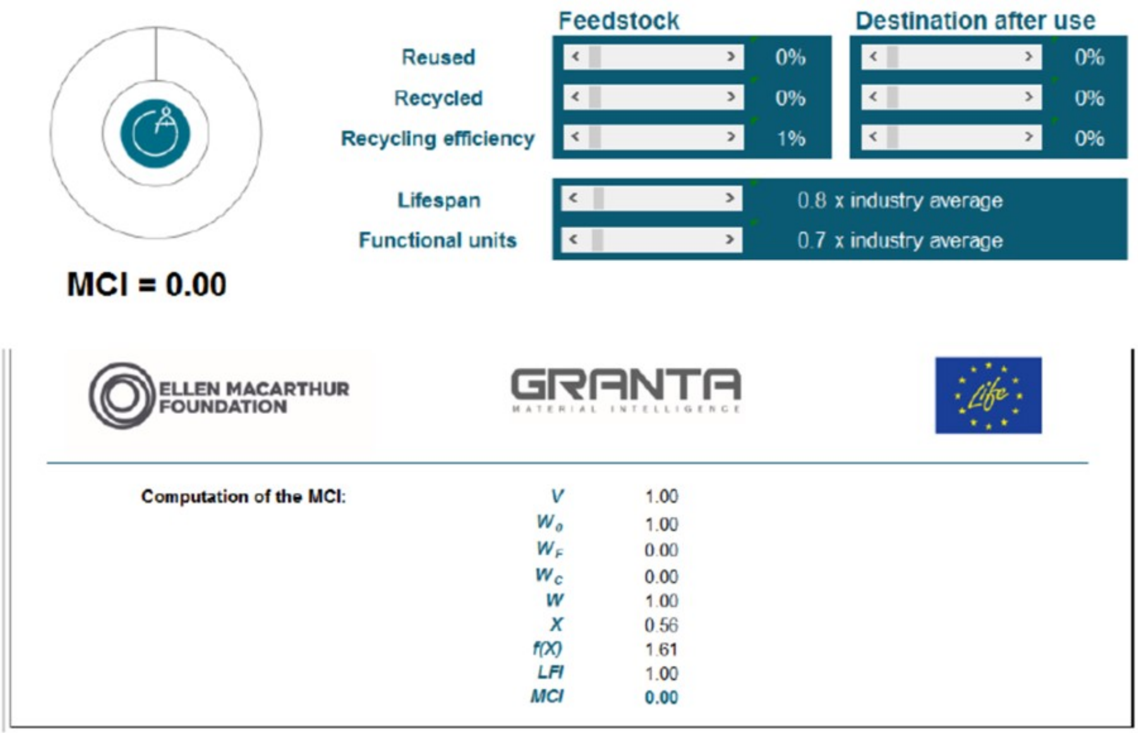

FIGURE 4
Calculation of the MCI for the PVB
Source: Own elaboration.

Therefore, the lifetime value, which is the same as that in the previous simulation, is respected, and the functional unit value is modified to the 1,700 kg of PVB obtained with respect to the 8,000 kg processed from the windshield.

Circular Economy Toolkit

The results obtained from the CET enable the determination of possible modifications for improving the process's circularity. As the tool's description points out, the user must answer various questions to obtain the improvement potential by area. Figure 5 summarizes the data obtained via the CET.

The improvement potential was low in the "design, manufacture and distribution" stage for several reasons. The process does not present considerable material waste in its manufacturing stage, as it is almost entirely separated. The characteristics of the windshield have made it a product with high percentages of "technical material" (nondegradable), which contributes to the use of virgin materials during its creation. Notably, this stage focuses on the material (windshield), not the specific process.

The "usage" stage (by the customer) is at a low potential because failures in the product rarely occur, and the lifetime of the glass is very long.

In the "product repair or maintenance" stage, the potential is high because the cost of repair is small compared with the cost of the product and the ease of repairing the machinery in the process.

The "product reuse and redistribution" stage is characterized by medium potential because glass has a good market for second-hand sales and the material has a long lifetime.

The "remanufacturing or renewal of the product or its parts" stage indicates high potential. The average remanufacturing costs are the reasons for this result, as the process does not require significant costs. In addition, the collection costs to return the product to the factory are not relatively high because the transportation required to move the material does not incur significant costs in terms of logistics or fuel use. The parts of the windshield, the glass, and the PVB are easy to separate via the current process, meaning that these materials have no significant separation problems.

The "recycling of the product at the end of its life" stage has low potential because the characteristics of the process indicate that the tools used to obtain the calcine work efficiently, so the process does not require the use of more up-to-date machinery.

The "product as a service" stage has a medium improvement potential owing to the lack of market to sell the obtained product since the recovered glass does not function as a material associated with the provision of some service, such as rent or lease.

By analyzing these characteristics and their association with the results previously obtained, we can understand the relationships among them. First, the "use and recycling of the materials obtained (calcine and PVB) and processed (windshields) cannot be replaced because the main purpose of the process is to separate the components from the windshield. Second, the "optimization of the materials" is an area of opportunity because, with current technology, improvements could be made to increase its "continuous improvement" and achieve the desired effectiveness and productivity. Finally, in terms of the third point, "industrial symbiosis," this is a relevant strategy to create value. It is crucial to establish business connections that can lead to circular business opportunities.

An example is the calcine obtained, which is sold to another company when separated from the polymer. The only drawback of this current strategy for the recycling company is that it does not have an external relationship with any company that takes advantage of the PVB within its supply chain, which significantly complicates the use of this material.

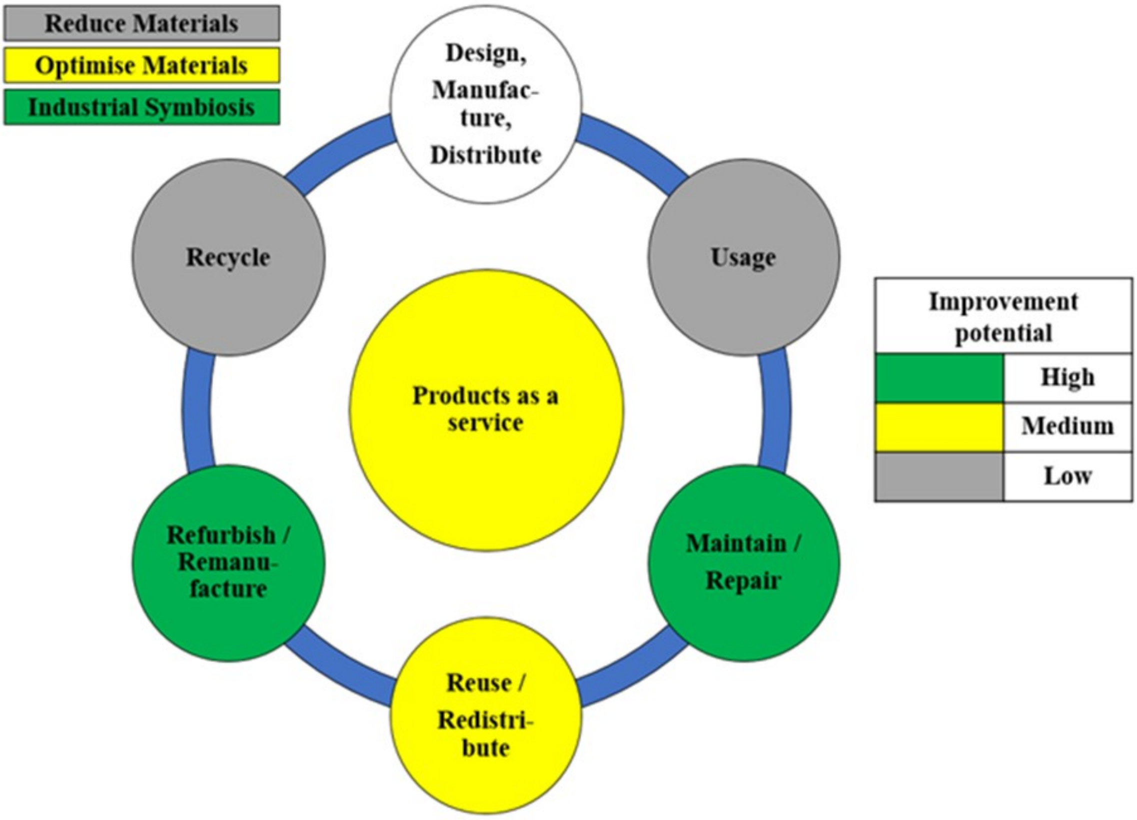

FIGURE 5
The Tool's Subareas Colored According to their Improvement Potential
Source: Own elaboration.

Proposed Strategies to Improve the Process

Figure 6 details the proposed modifications that increase the production of calcine and implement circular strategies to reduce the impact on the environment.

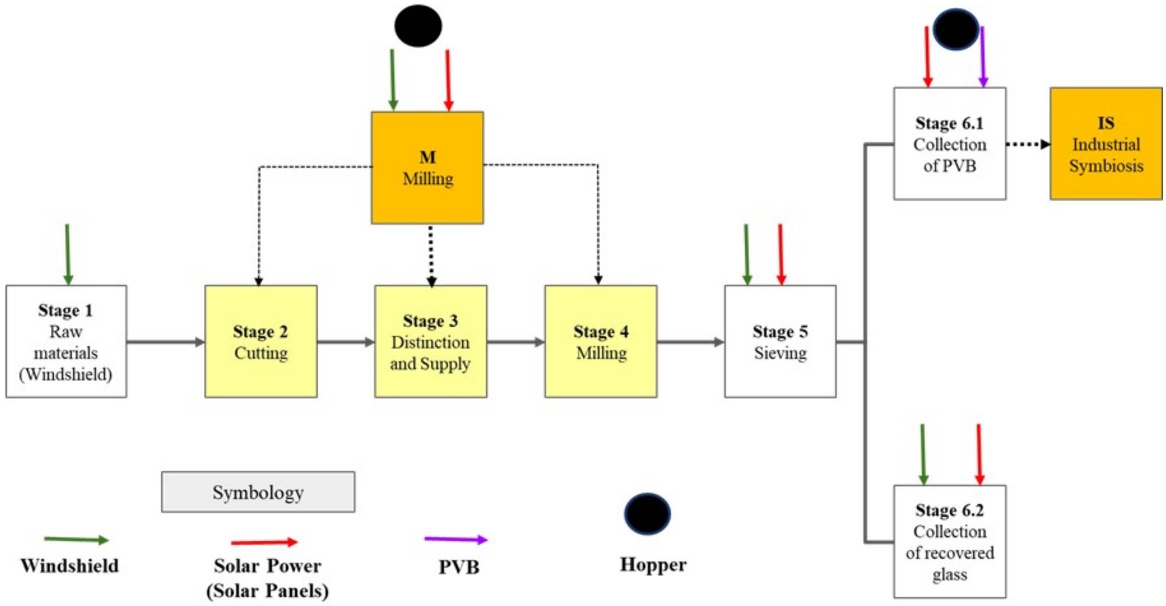

FIGURE 6
Modifications and Circular Strategies in the Windshield Delamination Process of the Recycling Company
Source: Own elaboration.

First, as mentioned earlier, the delamination process uses a considerable amount of water; therefore, to eliminate the water footprint, incorporating two dust extraction hoppers in the shape of large ducts has been proposed. This allows constant withdrawal of the dust from the grinding and screening of the windshield. In the actual design, water is supplied through small sprinklers to avoid the release of dust.

Second, to increase the production of calcine, the company has proposed replacing three phases of the process (windshield cutting, separation and feeding of the grind, and milling) by incorporating an innovative and larger mill that is able to perform the three mentioned phases in one stage. Through these modifications and considering the electricity consumption necessary to process the same 8,000 kg of windshield, it has been estimated that the carbon footprint would be 25 kg of CO2, which is 10% smaller than the value obtained with the current design. Table 2 summarizes the comparison of the processes with and without modifications.

TABLE 2
Comparison of the Main Characteristics of the Current and Integrated Processes with Possible Improvements

	Current process	Suggested process
Processed windshield	8 000 kg	8 000 kg
Obtained Calcine	6 300 kg	6 300 kg
Electrical consumption	62 kWh	54 kWh
Carbon footprint	28 kg CO_{2eq}	25 kg CO_{2eq}
Water footprint	144 L	0 L

Source: Own elaboration.

In addition, renewable energy can be integrated into the process by using photovoltaic solar panels. In this way, energy from fossil fuels would be replaced, so the carbon footprint would be eliminated, which is one of the goals of the CE. According to some studies, a photovoltaic solar panel provides 320 W of energy; therefore, to satisfy the daily electrical consumption in the retrofitting process, it would be necessary to install 15 photovoltaic solar panels. The initial cost would be approximately US$ 4,500.00. The average annual payment for electrical consumption is US$ 650.00, so the cost would be recovered in 3 years. Considering that the average lifetime of photovoltaic solar panels is 25 years, the economic savings would be remarkable for the company, even considering the maintenance expenses for the photovoltaic system.

Strategies to Recycle the Recovered PVB

Recycling PVB allows the material to be recovered with a purity of over 97%, which maintains mechanical properties comparable to those of virgin PVB, including impact resistance, transparency, mechanical stability and optical purity, with the additional advantage of reduced costs, since its price (US$ 0.25 to US$ 0.50 per kilogram) is significantly lower than that of virgin PVB (US$ 2.50 to US$ 4.50 per kilogram). However, the recycling process also presents technical challenges, such as the loss of plasticizers, which can affect the flexibility of the material. To overcome this disadvantage, methods such as the addition of compounds, such as dibutyl sebacate, have been implemented to help preserve the mechanical and optical properties of the PVB [21]-[24].

In geopolymeric applications, adding PVB improves the compressive strength and toughness of the material, increasing the impact resistance to 5.48 J/cm^2 in geopolymeric mortars. However, recent studies have also revealed that adding PVB can decrease flexural strength, suggesting that its use should be adapted to specific applications where impact resistance is prioritized over other mechanical properties. In the field of thermoplastics, recycled PVB has been mixed with low-density polyethylene (LDPE) and crushed glass, resulting in a material with greater rigidity and lower deformation, which is ideal for 3D printing processes [25]-[28].

In recent studies, recycled PVB has been shown to have a small particle size, facilitating its penetration into porous structures such as mortar. Furthermore, its low viscosity and fast drying speed increase its applicability. CO_2 diffusion tests have revealed that recycled PVB offers an effective barrier against CO_2 permeation, with a diffusion equivalent thickness exceeding the properties of the original PVB, thus contributing to sustainability in construction [29].

Another application of recycled PVB is its use in manufacturing silicon carbide (SiC) nanocrystals through a magnesium-thermal reduction process, which takes advantage of the silicon content of the glass that cannot be separated from the plastic and the carbon from the PVB structure. These nanocrystals have high thermal resistance and durability and are used as refractory materials and industrial components [30-32].

The reuse of PVB has been extended to produce sustainable separators for lithium-ion batteries. The recovered PVB is transformed into membranes that are durable and highly compatible with metallic lithium. These membranes have demonstrated a capacity of 120 mAh/g for 250 cycles, making them a viable and environmentally friendly alternative to commercial separators and contributing to sustainability in the battery industry [33].

Conclusions

Using the Ellen McArthur Foundation's circularity simulator and the information provided by the company about the processing conditions, a circularity index for the delamination of windshields was calculated. A high linear value was obtained for calcine recovery and PVB disposal. This is a consequence of the characteristics of the process since no byproducts are currently recycled or reused. Nevertheless, applying the principle of industrial symbiosis given by the CE, the PVB may be reused in other industries, so the circularity index would be improved depending on the capacity and efficiency of the chosen process. On the basis of the life cycle analysis, the current process for delaminating windshields has several environmental impacts. The carbon footprint is 28 kg CO_{2eq}, and the water footprint is 144 L for the delamination of 8,000 kg of damaged windshield. A retrofit that the company is considering consists of installing two dust extraction hoppers and a larger mill, which would decrease these indicators to 25 kg CO_{2eq} and 0 L for the carbon and water footprints, respectively. Moreover, if a photovoltaic system is installed, the electrical requirements of the process would be replaced by renewable energy (another principle of the CE), and the carbon footprint would decrease to zero. Additionally, the company would obtain economic savings, the cost would be recovered in 3 years, and the average lifetime of the photovoltaic solar panels is 25 years.

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Notes

* Research article

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