Resources, Conservation & Recycling Advances 30 (2026) 200344

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

Life cycle assessment to optimize alkali-activation of glass waste for sustainable construction materials

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ARTICLE INFO

Keywords:
Industrial glass waste
Consolidation processes
Circular economy
Environmental impacts
Sustainable production

ABSTRACT

This study investigates the valorisation of boro-alumino-silicate glass waste through alkali activation, proposing its reuse in the production of lightweight construction materials. The research aims to evaluate the environmental impacts of three different processing: (A) conventional cold consolidation at 40 °C for seven days, (B) a hybrid process involving 24-h pre-curing at 40 °C followed by microwave treatment (450 W, 5 min), and (C) an accelerated process involving 6-h pre-curing at 75 °C followed by the same microwave treatment. A gate-to-gate Life Cycle Assessment (LCA) was conducted using ReCiPe 2016 Midpoint (E) method to quantify environmental performance. The functional unit was defined as 1 kg of glass to produce consolidated material. Results indicate substantial differences among the processes: process A exhibited the highest overall environmental burden (77.9 kg CO_2 eq), while process B (11.2 kg CO_2 eq) and process C (2.9 kg CO_2 eq) showed significant reductions. Contribution analysis identified the consolidation phase as the dominant contributor to impacts, driven by electricity consumption and uncertainty analysis confirmed the robustness of the results. Monte Carlo uncertainty analysis confirmed the robustness of the results, with process C consistently emerging as a sustainable option.

The study highlights the potential of integrating mild alkali activation and microwave technology as a circular and energy-efficient strategy for the valorisation of pharmaceutical glass within the framework of sustainable material design.

1. Introduction

Pharmaceutical glass emerged as one of the most rapidly expanding categories within the glass containers sector (Kurtuluş et al., 2022; Tameni et al., 2025a). Once used, the generation and accumulation of pharmaceutical glass waste represent as a significant global concern. According to Corning data, approximately 136 million kilograms of Type I pharmaceutical glass are used each year in the manufacturing of pharmaceutical vials. However, due to fragmented and complex regional recycling regulations in waste disposal and the absence of any specific recycling targets most of the pharmaceutical glass is ultimately landfilled (Saadatpour et al., 2025; Polasani, 2024). Recycling pharmaceutical glass presents significant challenges, primarily due to its essential role as a container for drugs. Once in contact with pharmaceuticals, vials become biologically contaminated and consequently classified as hazardous or infect waste. The sterilization and reconditioning of pharmaceutical glass are more costly compared to simple landfill disposal or incineration (Hossain et al., 2025). However, both landfilling and incineration have significant drawbacks, including occupation of land resources and harmful gas emission. Furthermore, even when a purified fraction of pharmaceutical glass is recycled, the remelting process may compromise its rigorous chemical and physical specification, thereby rendering the use of pharmaceutical containers highly challenging.

Both the academia and industry have proposed alternative solutions for the recycling and reuse of pharmaceutical glass. SCHOTT, one of the leading manufacturers of pharmaceuticals, has recently established a pilot plant for closed-loop recycling of pharmaceutical glass (Schott, 2024). However, despite these advancements in circular economy practices, the approach remains limited, as only FIOLAX® clean glass can be returned to the melting tank to produce new pharmaceutical glass tubing (Kaiser and Bayer, 2024). No alternative is proposed for the contaminated fractions, which therefore only be considered eligible for valorisation through open-loop recycling process (Delbari and Hof, 2024), enabling its reuse in the production of materials distinct from original applications.

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https://doi.org/10.1016/j.rcradv.2026.200344

Recent studies have demonstrated that medical glass can be effectively valorised as a resource in construction materials (Murillo et al., 2025). Thanks to its high silica content and beneficial properties as high hardness and low permeability (de Azevedo et al., 2017), waste glass can be utilized as a binder to partially substitute cement or as a component of aggregates (Ho and Huynh, 2022), contributing to a sustainable practice. Glass used in concrete does not require melting, thereby reducing energy consumption, and its processing is simplified, eliminating the need for extensive sorting and cleaning operations (Guo et al., 2020). However, the replacement percentage of glass is partial, with most of the study that indicate the 10 wt% as optimum replacement level (Zeybek et al., 2022).

Beyond concrete, waste glass can be utilized in the synthesis of geopolymers and alkali activated materials, both representing sustainable cementing systems (Provis, 2018) that offer an alternative to Ordinary Portland Cement. These materials can be produced from a wide range of aluminosilicate precursors, primarily metakaolin and fly ash, dissolved in highly alkaline solutions (Luukkonen et al., 2018). In most studies, glass - regardless of its chemical composition - has been predominantly employed as an aggregate rather than as a primary precursor (Liu et al., 2019; Zhu et al., 2024). Pioneering works on the utilization of waste soda lime glass as exclusive precursor was conducted by Cyr and cooperators (Cyr et al., 2012; Idir et al., 2020), who demonstrated that, at room temperature, weakly concentrated alkaline hydroxides (< 3 mol/L) are sufficient to induce the surface dissolution and subsequent hardening.

Notably, mild alkali activation of boro-alumino-silicate (BASG) pharmaceutical glass proceeds via a mechanism distinct from conventional geopolymerisation, as it does not involve complete dissolution of the precursor materials followed by subsequent recondensation. Instead, the cold consolidation of glass powder suspension occurs via condensation reactions among surface silanol groups. Other phases, including carbonates formed from the reaction of alkalis with atmospheric CO_2 and an amorphous gel containing borates, silicates, and aluminates resulting from partial glass network dismantling, play a negligible role in the structural stability of the materials (Tameni et al., 2025b). The resulting materials can be employed in the construction and building sector, as the ratio of mechanical strength and density is comparable to that of structural lightweight cement or Plaster of Paris (Tameni et al., 2025b). Nevertheless, one of the principal limitations of alkali-activated materials is the long setting time, which can hinder practical application. In fact, 'cold consolidation' treatments are typically carried out for 7 days at 40 °C. To accelerate this stage of the process, a microwave-assisted process is implemented (Carollo et al., 2025; Tameni et al., 2025b).

The research compares the traditional process with two different thermal pre-treatments (6 h at 75 °C and 24 h at 40 °C), each followed by a five-minute treatment at 450 W in a household microwave oven, in order to achieve complete solidification. The treatment accelerates the hardening process, and it is expected to improve the mechanical properties of the materials while reducing environmental impacts of the processes. The research questions can be summarized as follows:

- How do the mechanical properties of the materials change when different thermal pre-treatments are added to the conventional process?
- How do the environmental impacts change when different thermal pre-treatments are added to the conventional process?

The Materials and Methods section outlines the methodological framework adopted in this study, describing the preparation of the samples, the procedures used to analyse their mechanical properties, and the approach for the environmental impact assessment. The Results and Discussions section reports the main outcomes of the research, focusing on the most relevant trends observed in the mechanical behaviour of the materials and in the corresponding environmental performance. Special attention is dedicated to the uncertainty analysis associated with the environmental evaluation. The assumptions, and methodological limitations are examined in order to provide a critical interpretation of the findings. Finally, the Conclusions section summarises the insights gained from the study and reflects on their broader implications within the fields of sustainable materials and circular economy. Possible directions for future research are also outlined.

2. Materials and methods

2.1. Alkali activation process and samples production

The primary raw material employed in all the formulations considered in this investigation is 'highly contaminated' or waste boro-alumino-silicate pharmaceutical glass. 'BASG waste', consisting of BASG glass cullet contaminated with metal particles from needles and grinding tools, was kindly supplied by Stevanato Group (Piombino Dese, Padova, Italy). The material was already provided in the form of fine powders. The chemical composition of starting material is reported in Table 1.

The glass powders were sieved to achieve a particle size <75 μm (IRIS FTL-0300, Filtra Vibraction, Badalona, Spain). The alkali activation was performed by suspending BASG powder in a blended solution (2.5 M) of sodium hydroxide (NaOH, Sigma-Aldrich, Gillingham, UK). Liquid-to-solid ratio was fixed at 0.50 for all formulations. The alkaline solution was prepared by dissolving 50 gof NaOH pellets in 0.5 L of distilled water at room temperature. After 3 h of low-speed mechanical stirring (500 rpm), the slurries were first poured into silicone molds of dimensions 45 × 40 × 10 mm3 and 10 × 10 × 10 mm3 (open mold) and then subjected to three different consolidation treatments (processes A, B, C). The curing treatments can differ in temperature, duration, and environmental conditions, all of which play a crucial role in determining the stability and performance of the final products. The three consolidation processes considered in this investigation are reported below:

A. The activated glass suspensions were poured into silicone molds after mechanical stirring and were left to dry for seven days in a Bio-tech stove (Biomedica Elettronica, Padova, Italy) at nearly room temperature (40 °C) in a condition of 'cold consolidation' (Tameni et al., 2025a).
B. To reduce the time-consuming nature of the hardening phase, the use of microwave technology was investigated. Recent studies on metakaolin have demonstrated that microwave heating can be effectively applied to dry activated slurries, significantly reducing both curing time and energy consumption (Aschoff et al., 2024). It is widely recognized that MW heating is more efficient, minimizes temperature gradients through volumetric heating, and, most importantly, requires less energy (Horvat et al., 2023). In addition, as demonstrated by Tameni and al., microwave heating leads to improved mechanical resistance of the materials produced by alkaline activation (Tameni et al., 2025a). Upon activation, the specimens were left to rest for 1 day at 40 °C in a Bio-tech stove and then subjected to microwave heating (microwave oven Samsung MS23F300EEK, Samsung Electronics Italia S.p.A, Milano, Italy) for 5 min at 450 W to finalize hardening.
C. The experimental conditions and methodologies are comparable to those outlined in process B but instead of 1 day at 40 °C, the activated suspensions were pre-treated in the stove for 6 h at 75 °C. As in the previous process, the drying was finalized by heating with a microwave oven for 5 min at 450 W.

2.2. Samples characterization

The geometric density (ρ_{geom}) of consolidated samples was evaluated by considering the mass-to-volume ratio of cubic samples (10 mm × 10 mm × 10 mm). The mass of the samples was measured with an analytical

Table 1
Chemical composition (expressed in wt%) of the starting waste glass.

Oxides	Al_2O_3	BaO	CaO	Fe_2O_3	K_2O	NaO	SiO_2	B_2O_3	Traces
BASG Waste	6.3 ± 0.3	0.54 ± 0.05	1.0 ± 0.1	3.6 ± 0.5	1.1 ± 0.1	6.8 ± 0.5	72 ± 1	8.5 ± 0.03	< 0.16

balance and the volume with a digital calliper.

The compressive strength of the cubic dried samples (both dense and porous) was measured according to the standard UNI EN 826 (UNI, 2013) using a Universal Testing Machine (Quasar 25, Galdabini S.p.a., Cardano al Campo, Italy), operating at a crosshead speed of 0.5 mm/min. Five samples were tested for each formulation.

2.3. Life cycle assessment

The environmental impact assessment was carried out using the Life Cycle Assessment (LCA) methodology. This approach follows the principles outlined in ISO 14,040 (ISO, 2006a) and ISO 14,044 (ISO, 2006b), along with the requirements of EN 15,804:2012+A2:2019 (CEN, 2019), which is specific to the construction sector. The study was structured into four main phases: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIS), and Life Cycle Interpretation of Results (LCIR). The goal of the study is to compare alternative processing routes with respect to their environmental impacts and process-level circularity. The system boundary is defined as gate-to-gate, encompassing all steps from raw material input to final product consolidation. Inventory data for the foreground processes were collected from measurements and process documentation, while background data were obtained from the life cycle database. Impact assessment was conducted using the ReCiPe 2016 Midpoint indicators, and uncertainty was evaluated through a Monte Carlo simulation.

2.3.1. Goal and scope definition

The aim of this research was to quantify the environmental impacts associated with three glass recycling processes, as described in Section 2.1. The produced material is intended for use as an insulating material in construction, and the functional unit considered is 1 kg of glass (Battiston et al., 2025). The system boundaries were limited to the alkali activation process, reflecting a “gate-to-gate” comparison of the different recycling processes. The up-stream and down-stream phases are excluded because the aim is to measure only the impacts associated to the processes. The starting assumption for this LCA study is that for all processes, the product maintains the same characteristics during the usage phase and has the same end-of-life. Other performance aspects of the material, such as its chemical, physical, and mechanical properties, were already addressed in the analyses discussed in Section 3.1.

2.3.2. Life cycle inventory

The LCI involves a detailed quantification of all inputs and outputs associated with each stage of the process, with respect to the functional unit (FU) established during the goal and scope definition. Each process is analysed step by step with the aim of identifying the resources that enter the system—such as raw materials, natural resources, and energy—and the outputs generated at each stage, including waste, by-products, and emissions. Once these inputs and outputs have been identified, they are described in detail and quantified to provide a comprehensive understanding of the material and energy flows throughout the process. The data collected, along with the types of sources used for each entry, are summarized in Table 2.

The main data used in this study were obtained from analyses carried out in the laboratories of the University of Padova. The collected information was used to estimate both the transportation requirements, and the type and amount of energy consumed in the process. The distance considered corresponds to that between the city of Padova, where the treatment takes place, and Piombino Dese, where the company supplying the glass waste is located. Transportation was modelled using data from the Ecoinvent 3.10 database, specifically the entry “Transport, freight, lorry >32 t, EURO5, cut-off, system”. Energy consumption was estimated based on the nominal values reported in the equipment manuals and later compared with literature data for similar devices to ensure consistency. Electricity consumption was modelled using the dataset “Electricity, low voltage (IT), market for, APOS, system” from the Ecoinvent 3.10 database, which represents the average Italian national electricity mix delivered at low voltage. This dataset includes the contribution of the different electricity generation technologies present in the Italian grid (mainly natural gas, hydropower, solar, wind, and other minor sources) and was selected as it represents the most appropriate background scenario for processes assumed to occur in Italy.

Table 2
Data inventory for LCA of alkali activation processes related to FU – 1 kg of glass produced.

Phase	Data			Unit	Source
	Process A	Process B	Process C		
1. Glass waste arrival	1	1	1	Kg	Primary data
	30	30	30	Km	Secondary data
2. Sieving	0.1	0.1	0.1	kWh	Secondary data
3. Alkali activation	0.5	0.5	0.5	Kg	Primary data
	0.15	0.15	0.15	kWh	Secondary data
4. Consolidation	134.4	19.2	4.8	kWh	Secondary data
5. Microwaves		0.0375	0.0375	kWh	Secondary data

2.3.3. Life cycle impact assessment

The environmental impacts of the life cycle were assessed using SimaPro 10.1.0.4 software (Simapro, 2024). The ReCiPe 2016 Midpoint (E) V1.04 / World (2010) E method (ReCiPe, 2024) was chosen, as it allows a multidimensional evaluation of environmental performance. The Egalitarian (E) perspective aligns with a more precautionary view, as it considers long time horizons and a low tolerance threshold for environmental risks. This approach provides a comprehensive and multidimensional assessment of the environmental performance of the analysed processes, offering a detailed and comparable overview of the various impacts associated with the studied systems. The potential influence of alternative ReCiPe 2016 perspectives (Hierarchist or Individualist) was qualitatively considered. Although the choice of perspective may affect absolute impact values, it is not expected to alter the relative ranking of the assessed options (A, B, and C), as the comparison is primarily driven by differences in foreground process efficiencies rather than by shifts in impact category weighting.

All 18 midpoint impact categories included in this method were analysed in this study, including: global warming (GWP), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation – human health (OFHH), fine particulate matter formation (FPMF), ozone formation – terrestrial ecosystems (OFTE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), human toxicity – carcinogenic (HCT), human toxicity – non-carcinogenic (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS), and water consumption (WC).

2.3.4. *Life cycle interpretation of results*

The interpretation is carried out by assessing whether the results obtained are reasonable and consistent with the expected environmental performance. This step involves a critical review of the data quality, completeness, and representativeness, ensuring that the results accurately reflect the life cycle of the product or process. An uncertainty analysis is also conducted to evaluate the potential influence of data variability and gaps on the reliability of the environmental impact profiles. This analysis helps identify which parameters or processes have the greatest effect on the results, highlighting the robustness of the conclusions and guiding any necessary adjustments or further investigations.

3. Results and discussions

3.1. *Mechanical properties*

The alkali activated materials are characterized in terms of density and mechanical performance. Indeed, the obtained materials can be regarded as potential substitutes for conventional construction materials only if their properties exhibit a satisfactory correspondence with those commercially available. With the raw material, alkaline activator molarity, and liquid-to-solid ratio fixed, the development of compressive strength is observed to be governed by the curing conditions.

Samples subjected to oven curing for 7 days at 40 °C (case A) exhibited the lowest performance among all tested conditions, as reflected in both compressive strength ($\sigma_c = 10.3$ MPa) and geometrical density measurement ($\rho_{geom} = 1.26 \pm 0.02$ g/cm^3). Prolonged low-temperature curing is detrimental for both structural performance and environmental sustainability. However, despite their limited mechanical performance, these materials are still comparable to low-density refractory bricks (Fig. 1) suggesting that they could be used in applications where high strength is not critical.

Optimizing the curing strategy through the introduction of microwave treatment (case B and C) enables the production of materials with significantly improved compressive strength. It is generally acknowledged that microwave (MW) heating exhibits superior efficiency, mitigates the development of temperature gradients through volumetric energy distribution within the material, and, most notably, entails a reduced overall energy demand (Horvat et al., 2023). As demonstrated by Tameni et al., the improvement in mechanical strength can be attributed to enhanced carbonation occurring during the consolidation process. Microwave irradiation appears to promote the involvement of alkali cations (Na^+) in the formation of hydrated carbonates, resulting in a less depolymerized and consequently more stable gel structure (Tameni et al., 2025a).The pre-curing period, during which the materials are maintained in the oven prior to microwave treatment, exerts a modest influence on the final properties of the materials. Case B ($\sigma c = 20.3$ MPa), in which the materials undergo a 24 h pre-curing at 40 °C, exhibit slightly higher compressive strength compared to case C ($\sigma c = 18.9$ MPa), where the samples are treated only 6 h at 75 °C. Both samples exhibit a partial overlap with the properties of Plaster of Paris. More notably, their compressive strength values fall within the range typically associated with structural lightweight concrete, while maintaining lower densities, respectively 1.23 g/cm3 and 1.25 g/cm3 for case B and C, respectively. This combination of mechanical performance and reduced weight highlights the potential of these materials for application that required adequate strength and lightweight characteristics.

The mechanical compressive strength values obtained in this study are consistent with those reported in the literature for the alkali activation of glass with various chemical compositions. For instance, Redden et al. investigated the alkali activation of by-products from industrial and highway safety glass bead manufacturing using NaOH in a concentration between 4 and 8 mol/L (Redden et al., 2014). For samples activated at the lower14 concentration - comparable to those produced in this investigation - the reported compressive strength ranged from 17 to 21 MPa. Moreover, the compressive strength of alkali activated soda-lime-silica glass is highly variable, depending on the type of activator (e.g. sodium silicate or sodium aluminate solutions) and curing time and temperature. For example, You et al. reported compressive strength values It may vary from slightly above 10 MPa (You et al., 2024) to 22–29 MPa (Ramteke et al., 2024). Treating flat, hollow, and windshield soda-lime glass with 3 mol/L of KOH solution, it has been found that a high compressive strength, around 50 MPa, is achieved regardless of the glass type (Idir et al., 2020). To the best of the authors' knowledge, no previous studies have investigated alkali activation of cold consolidated materials based on pharmaceutical boro-alumino-silicate glass. Overall, these findings highlight that the compressive strength of samples in this study is consistent with the most data reported in the literature, despite differences in the hardening process and the type of alkali activator used.

According to the obtained results, alkali activated materials from waste pharmaceutical glass are suitable for significant practical applications, particularly in the construction and environmental sectors.

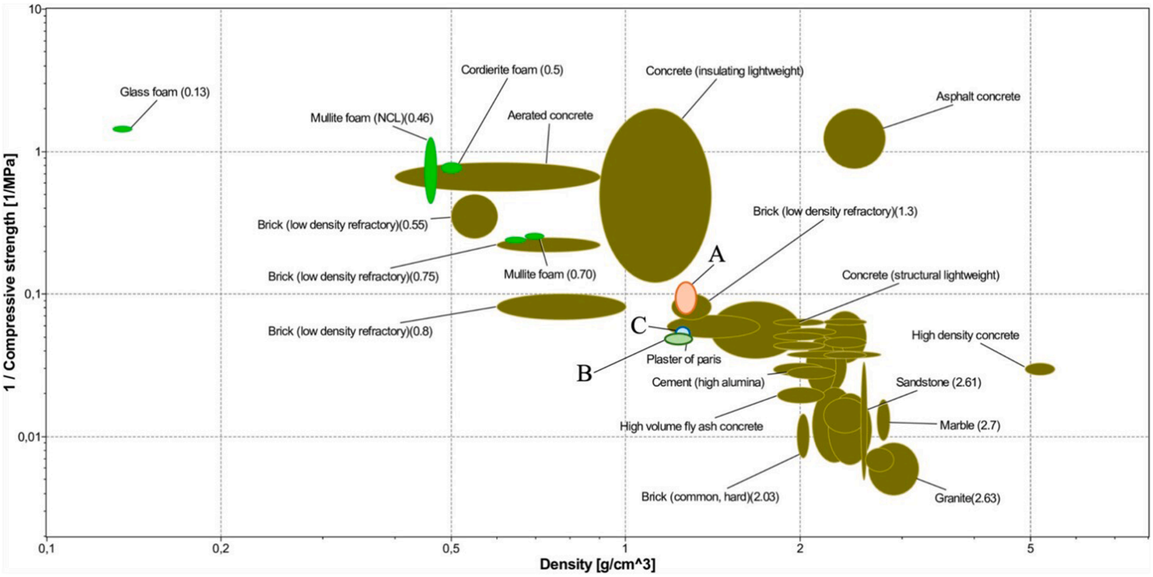

Fig. 1. Graph illustrating the trade-off between compressive strength and density of lightweight products (CES software package) in comparison to A, B, C samples.

These materials can be effectively used in structural concrete and precast elements such as tiles, pavers, and bricks, offering a sustainable alternative to conventional building materials. Furthermore, this easily implemented approach contributes to waste glass valorisation and reduced environmental impact (Ibrahim et al., 2023; Pederson et al., 2025).

3.2. *Life cycle impact assessment results*

The results of the LCIA refer to 1 kg of input glass and are described in Table 3. Each row corresponds to a specific impact category, as defined by the ReCiPe method, while the columns show the calculated values for each of the three processes (A, B, and C), along with their respective units of measurement. All reported values are positive, indicating that each process contributes incrementally to potential environmental impacts. No avoided impacts or environmental benefits are observed, which would otherwise be represented by negative values. A clear trend can be seen across nearly all categories, with process A showing the highest environmental burden. For example, regarding GWP, process A generates approximately 77.9 kg CO_2 equivalent, while process B contributes 11.23 kg CO_2 eq and process C only 2.9 kg CO_2 eq.

To assess the plausibility of the reported magnitude, a simple cross-check was performed by converting the electricity consumption associated with this stage into CO_2-equivalent emissions using the Italian electricity mix assumed in the background database. This calculation confirms that the resulting emissions are of the same order of magnitude as the GWP value obtained through the LCIA, thereby supporting the consistency between the life cycle inventory data, the applied emission factors, and the reported results. Although electricity is the main contributor to the GWP, its influence on other impact categories is comparatively smaller. This is related to the emission profile of the Italian electricity mix in the Ecoinvent dataset, where the dominant contributions are associated with fossil-based CO_2 emissions, while emissions of acidifying or eutrophying substances are relatively lower. Consequently, the alkali activation stage primarily affects climate change results in the present assessment. Other impact categories also present a similar hierarchy. Marine eutrophication shows particularly large differences, with process A reaching 6112 kg 1,4-DCB, compared to 895.5 kg 1,4-DCB for process B and 243.3 kg 1,4-DCB for process C. Across all these metrics, process C consistently appears as the most environmentally sustainable option, showing substantially lower impacts than processes A and B, while process B generally performs better than process A but remains higher than process C.

Overall, the assessment highlights significant differences in environmental performance among the three processes. Process A, although possibly advantageous in operational terms, contributes disproportionately to environmental pressures across multiple categories. Process C, on the other hand, represents the most sustainable alternative, minimizing emissions, resource use, and other impacts, and offering a clear opportunity for reducing the overall environmental footprint.

Table 3
LCIA results of processes A, B, and C calculated with recipe method.

Impact categories	Process A	Process B	Process C	Unit
GWP	77.9	11.23	2.9	kg CO_2 eq
SOD	4.582 E-05	6.629 E-05	1.728 E-06	kg CFC11 eq
IR	4.276	0.6274	0.1711	kBq Co-60 eq
OFHH	0.1242	0.01797	0.004689	kg NOx eq
FPMF	0.05221	0.007561	0.001978	kg PM2.5 eq
OFTE	0.1346	0.01947	0.005079	kg NOx eq
TA	0.1516	0.02192	0.005714	kg SO_2 eq
FE	0.01206	0.001753	0.0004642	kg P eq
ME	0.0009827	0.0001458	4.114 E-05	kg N eq
TET	346.8	50.54	13.5	kg 1,4-DCB
FET	1.185	0.1732	0.04672	kg 1,4-DCB
MET	6112	895.5	243.3	kg 1,4-DCB
HCT	375.8	54.71	14.55	kg 1,4-DCB
HNCT	5042	738.1	199.9	kg 1,4-DCB
LU	0.8444	0.1243	0.03421	m^2a crop eq
MRS	0.07139	0.0104	0.002775	kg Cu eq
FRS	29.29	4.221	1.087	kg oil eq
WC	0.6425	0.09414	0.02557	m^3

Process A consistently exhibits the highest values in nearly all categories, confirming that it imposes the greatest environmental burden overall. The elevated contributions across categories such as global warming potential, acidification, and ecotoxicity indicate that process A is associated with higher emissions, greater resource consumption, and more substantial environmental pressures compared to the other alternatives. Process B, on the other hand, shows lower values in all categories relative to process A. While it still generates measurable impacts, these are moderate in comparison, suggesting that process B has a reduced environmental footprint and represents an intermediate option in terms of sustainability. Process C emerges as the most environmentally favourable alternative. This pattern highlights the potential benefits of adopting process C, not only in terms of mitigating environmental impacts but also in contributing to more sustainable production practices. The observed ranking among processes is also coherent with previous LCA investigations on alkali-activated glass systems (Battiston et al., 2025), where thermal treatments were identified as the primary contributors to global warming potential under gate-to-gate boundaries.

To demonstrate if the observations align with the research objectives, a contribution analysis was carried out. This analysis breaks down the total environmental impact of each process into its individual phases, making it possible to identify which steps contribute most significantly to the overall impact. Understanding these contributions is essential for highlighting areas where improvements could be most effective and for guiding strategies aimed at reducing environmental burdens.

Fig. 2 shows the results of the contribution analysis for processes A, B, and C. In all three cases, the consolidation phase accounts for the largest share of environmental impact. This is primarily due to the high energy consumption required during this stage, which drives emissions and resource use across multiple impact categories, including global warming potential, acidification, and ecotoxicity. The prominence of the consolidation phase indicates that energy-intensive operations are the main drivers of environmental impacts in these processes, suggesting that optimizing energy use or adopting cleaner energy sources could significantly reduce the overall footprint. The assumed electricity mix can significantly affects the absolute magnitude of the calculated impacts, particularly for electricity-intensive stages such as alkali activation. Changes in the grid mix, such as greater penetration of renewable energy sources, would likely reduce the overall impacts, especially for categories like GWP and water consumption. A sensitivity analysis was performed to assess the influence of the electricity source on the environmental results. In this analysis, the baseline Italian electricity mix was replaced with electricity generated from photovoltaic solar energy. The results show that the contribution associated with electricity consumption decreases considerably when photovoltaic electricity is used. For example, the contribution of electricity to GWP decreases from approximately 11.9% in the baseline scenario to about 1.7% in the photovoltaic scenario. Similar reductions are observed for other impact categories, such as freshwater eutrophication (from about 63.6% to 9.3%) and water consumption (from about 55.3% to 8.1%). Although the absolute magnitude of the impact changes, the relative contribution of the different production phases remains similar. This result is consistent with the expectation that the relative ranking of the processes would remain largely unchanged, as the main differences between the investigated systems are primarily driven by process efficiencies rather than by the choice of electricity source.

Other phases contribute less to the total impact, but their cumulative effects are still relevant. For example, material arrival and preparation phases generate measurable impacts through electricity consumption, minor emissions, and small amounts of waste. Although these

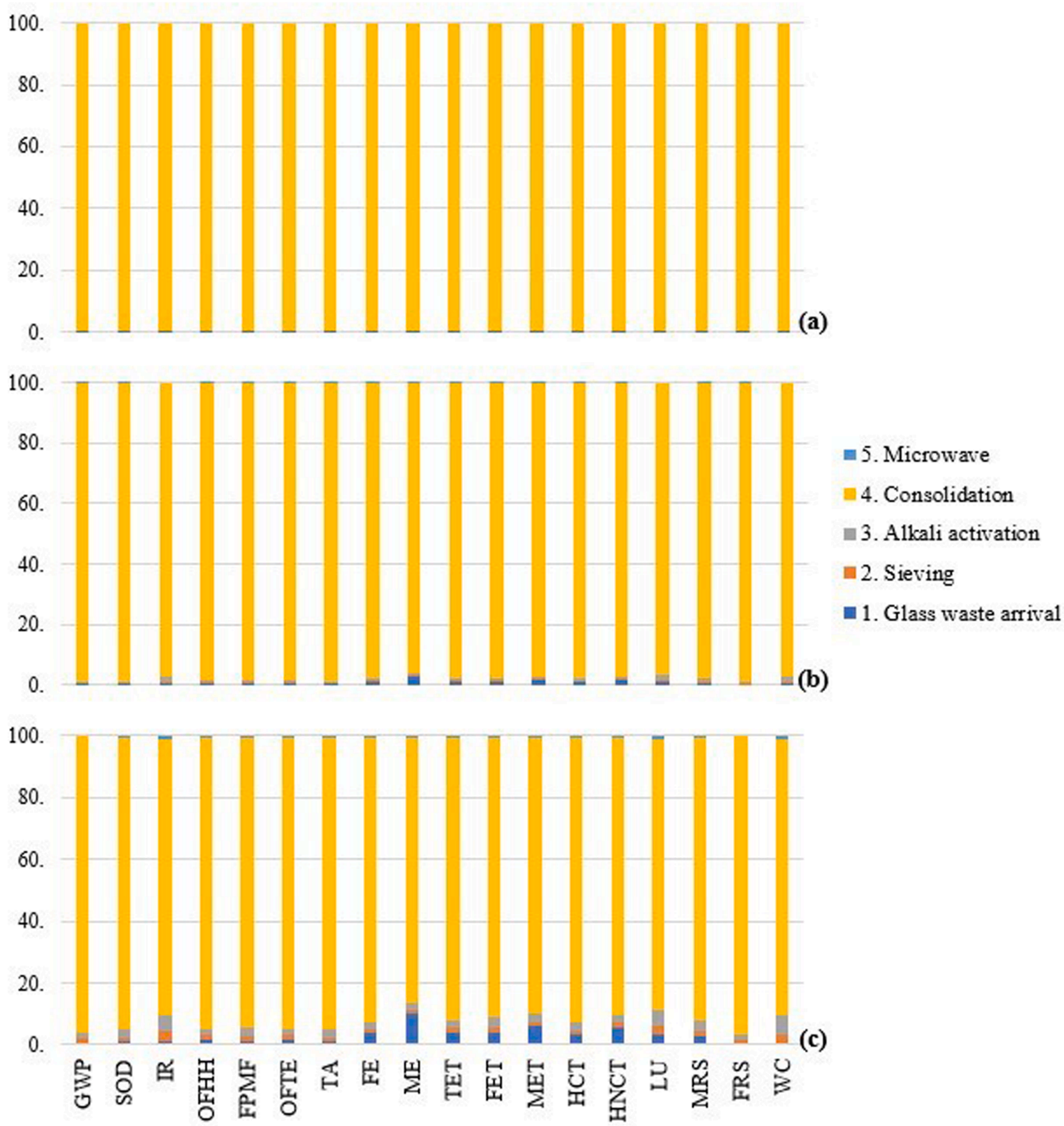

Fig. 2. Contribution analysis results of processes (a) A, (b) B, and (c) C calculated with recipe method.

contributions are smaller than those of the consolidation phase, they highlight the importance of considering the entire process when implementing mitigation measures.

In summary, the contribution analysis confirms that process A has the highest overall environmental impact. It also explains why this occurs, showing that the consolidation phase is the main contributor across all processes.

The environmental implications of pharmaceutical glass management have been discussed in recent literature. For instance, Hossain et al. highlight that sterilization and reconditioning of contaminated pharmaceutical glass are often more energy- and cost-intensive than disposal options, which explains the continued reliance on landfill and incineration despite their environmental drawbacks. Similarly, Saadatpour et al. and Polasani emphasize how fragmented regulations and the absence of specific recycling targets limit the effective circular management of pharmaceutical glass waste. The present study aligns conceptually with sustainable cementitious systems discussed by Provis and Luukkonen et al., who identify alkaline activator production and thermal curing as the main environmental hotspots in alkali-activated materials. Consistent with these findings, the contribution analysis performed in this study confirms that the consolidation phase - dominated by electricity consumption - represents the principal driver of environmental impacts across all categories.

3.3. *Uncertainly results*

The results of the LCIA are clear: the adoption of microwave heating in processes B and C leads to shorter processing times and a notable improvement in environmental performance. However, it is important to acknowledge that some input data are subject to uncertainty, which could influence the confidence in the results, particularly when comparing processes B and C, whose environmental impacts are relatively close. The LCIR had to consider the potential effects of this uncertainty. A contribution and probabilistic analysis were conducted to assess how the variability in input parameters may propagate through the life cycle assessment and affect the final conclusions. In this study, a Monte Carlo simulation was performed in SimaPro, with 1000 iterations to capture a wide range of possible outcomes. Key foreground inventory parameters were assigned lognormal distributions, following common LCA practice, with ranges reflecting both data variability and measurement uncertainty. Background processes used the uncertainty distributions provided in the life cycle database. By repeatedly sampling input values according to their probability distributions, the simulation provides a probabilistic understanding of the environmental performance of each process rather than relying solely on fixed values.

The results of the simulation are shown in Fig. 3. In 100% of the iterations, process C exhibits lower overall environmental impacts, demonstrating the robustness of the comparison even when uncertainties are considered. The only exception is the water consumption category, which is particularly sensitive to variations in input data. In this case, the difference between processes B and C is smaller, although process C generally still maintains a lower impact. Water consumption is the exception, largely due to water use embedded in the electricity background processes. Because of overlapping uncertainty ranges in electricity-related water flows, differences between the processes are less clear for this category, even though the overall ranking remains consistent for the other impact indicators. This highlights the importance of carefully examining categories that are strongly affected by data variability, as they can influence specific aspects of the analysis more than others.

The uncertainty analysis reinforces the reliability of the results. Even accounting for potential variability in input data, process C remains the environmentally preferable option. This confirms that the observed differences are not the result of uncertain data but reflect actual differences in performance between the processes. This analysis emphasizes the need for accurate data collection and careful monitoring of high-impact process phases, ensuring that mitigation strategies and process optimizations are based on a solid, evidence-driven assessments.

4. Conclusions

The primary objective of this study is to evaluate and compare alternative processing routes in terms of environmental performance and process-level circularity. The LCA results provide quantitative evidence to support this objective by identifying key contributors to environmental impacts, such as electricity consumption in consolidation, and by highlighting differences among processes in terms of resource efficiency and water use. By focusing on these hotspots, the analysis informs recommendations for process selection and potential improvements, thereby directly linking the LCA findings to the overall study goals. This study demonstrated the feasibility of reusing pharmaceutical boro-alumino-silicate glass waste through alkali activation under different thermal curing conditions. In comparison with previously reported glass-based alkali-activated systems, the present approach extends applicability to contaminated pharmaceutical streams, contributing to both waste diversion and low-carbon material development within a circular economy framework.

Three consolidation processes were compared to evaluate their mechanical performance and environmental impact. From a mechanical point of view, the curing method proved to be a key factor influencing material properties. The conventional cold consolidation process (A) produced the lowest compressive strength and density, while the modified routes (B and C), including thermal pre-treatment and heating, significantly improved performance. The LCA highlighted a strong correlation between energy demand and environmental performance. Process A showed the highest impacts, whereas processes B and C reduced emissions to 11.2 kg CO_2 eq and 2.9 kg CO_2 eq, respectively. Energy consumption during consolidation emerged as the main contributor to the overall impact. A sensitivity analysis using electricity generated from photovoltaic solar energy confirmed that although the absolute magnitude of impacts may decrease under a low-carbon electricity supply, the relative ranking of the processes remains largely unchanged. This observation is coherent with the energy-efficiency advantages of microwave heating reported by Horvat et al. and with the mechanical improvements observed in microwave-assisted alkali activation by Tameni et al. Overall, the results confirm trends identified in the literature regarding the importance of curing energy in alkali-activated systems, while extending current research to a contaminated pharmaceutical glass stream that is typically excluded from closed-loop recycling scenarios.

In conclusion, the proposed approach offers a sustainable route for the open-loop recycling of pharmaceutical glass waste. By integrating mechanical characterization with a LCA, this study provides a more comprehensive assessment of the feasibility of open-loop valorisation routes for pharmaceutical glass waste. The process converts a hazardous material into lightweight, mechanically stable products suitable for the construction sector, supporting circular economy principles and contributing to lower environmental burdens. However, this study adopts a gate-to-gate system boundary in order to ensure a consistent and robust comparison among alternative processing routes.

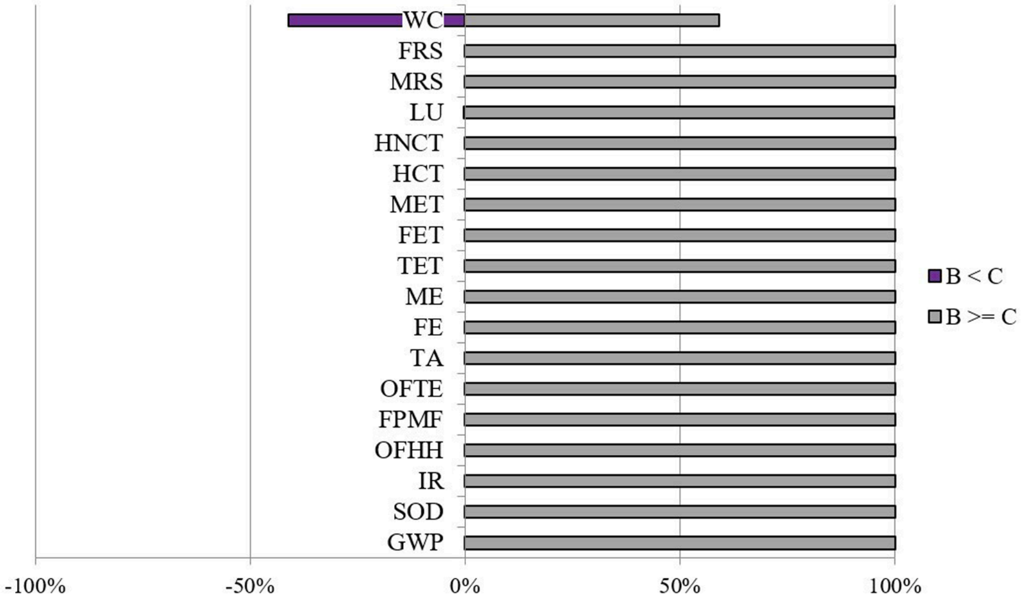

Fig. 3. Uncertainly results between process B and process C.

Accordingly, the circular economy implications derived from the present analysis are confined to the processing stage and should not be interpreted as representative of circularity performance over the full life cycle. The inclusion of downstream stages, such as disposal avoidance or alternative end-of-life management options, may further affect the overall interpretation of circularity-related outcomes. For instance, enhanced recyclability or the avoidance of final disposal could reinforce the advantages observed at the process level, whereas additional post-processing or treatment requirements could partially counterbalance these benefits. Therefore, a comprehensive life-cycle assessment incorporating downstream stages is recommended for future research to fully capture system-wide circularity effects.

Abbreviations

BASG: Boro-alumino-silicate glass
E: Egalitarian
BASG Boro-alumino-silicate glass
FE: Freshwater eutrophication
FET: Freshwater ecotoxicity
FPMF: Fine particulate matter formation
FRS: Fossil resource scarcity
FU: Functional Unit
GHG: Greenhouse Gas
GWP: Global warming
HCT: Human carcinogenic toxicity
HNCT: Human non-carcinogenic toxicity
IR: Ionizing radiation
LCA: Life Cycle Assessment
LCIA: Life Cycle Impact Assessment
LCIR: Life Cycle Interpretation of Results
LCT: Life Cycle Thinking
LU: Land use
ME: Marine eutrophication
MRS: Mineral resource scarcity
MSP: Medium-scale plant
MW: Micro-wave
OFHH: Ozone formation, Human health
OFTE: Ozone formation, Terrestrial ecosystems
SOD: Stratospheric ozone depletion
SSP: Small-scale plant
TA: Terrestrial acidification
TET: Terrestrial ecotoxicity
WC: Water consumption

Funding sources

This research was funded by the Italian Ministry of University and Research (MUR) in the framework of the GLASS_Trea.S.U.Res (GLASS-based TREAtments for Sustainable Upcycling of inorganic RESidues) project (PRIN 2022 PNRR project #P2022S4TK2).

CRediT authorship contribution statement

Anna Mazzi: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Elena Battiston:** Writing – original draft, Software, Investigation, Data curation. **Francesco Carollo:** Writing – original draft, Investigation, Formal analysis, Data curation. **Giulia Tameni:** Writing – original draft, Investigation, Formal analysis, Data curation. **Enrico Bernardo:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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