Heliyon 9 (2023) e19001

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Environmental performance of glass foam as insulation material from waste glass with the alkali activation process

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A R T I C L E I N F O

Keywords:
Glass foam
Waste glass
Upcycling
Life cycle assessment
Environmental impact

A B S T R A C T

Glass foams is an interesting option for the use of fractions of glass cullet otherwise destined to landfills. As building insulation materials, glass foams obtained by conventional processes have still some drawbacks in the purity of starting feedstock, which can be avoided by implementing an alkali activation process. Using the life cycle assessment methodology, the research analyses the potential impacts associated to the glass foam obtained from waste glass through the alkali activation in a laboratory scale plant with 'cradle to grave' perspective. The main phases included in the system boundaries are the downstream activities related to the transportation of glass waste and avoided landfill disposal, the production process to obtain the glass foam, and the upstream activities related to the transportation to potential use phase and the end of life. The life cycle environmental profile of glass foam is calculated starting from primary data integrated with the Ecoinvent database, and using the ReCiPe 2016 impact assessment method and the SimaPro software. Results demonstrate the greatest contribution on the overall environmental impacts due to the production, in which the main impacts are linked to electricity consumption for drying and firing and surfactant for the foaming. Sensitivity analyses clarify that consistent improvement in overall environmental impacts can be obtain with minimization of distances both between glass waste and production site, and between glass foam production and use; otherwise, different energy-mix and lower temperature in chemical processes have negligible effects in the environmental profile. The research reveals useful information to optimize the upcycling of glass foam production before moving on the industrialization: future investigations should involve the selection of biodegradable surfactants, from renewable sources.

1. Introduction

The dizzying increase in the resources consumption as well as the waste production has been reported to be likely to drive an ecological collapse [1]. Circular economy could assist in solving this dilemma: it's a system where resource use is optimized, seeking to always maintain it at its maximum value, diminishing both resource input, as materials and energy, and output, as product, byproduct, and waste [2]. Nevertheless, recycling alone might not be really sustainable, especially in case of downcycling: recovered materials are effectively convenient if in their second life they can replace virgin raw materials [3]. Therefore, recycled materials must have excellent chemical-physical performances, so upcycling is one of the technological challenges of the circular economy [4] and eco-design represents profitable solution [5].

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https://doi.org/10.1016/j.heliyon.2023.e19001
Received 6 March 2023; Received in revised form 24 July 2023; Accepted 4 August 2023
Available online 6 August 2023

Recycling in strict sense ('closed loop') involves the reuse in articles equivalent to the original one, in the hypothesis of no degradation of materials. Such hypothesis is far from being real, and recycling is accompanied by a certain loss of value ('down-cycling'), as shown by cellulose (passing from high quality office paper to cardboard [6]) or PET polymer (passing from containers to textile fibers [7]).

Unlike PET, glass is not subject to degradation of the molecular structure, upon remelting, so it can be recovered indefinitely without losing its properties [8]. '100% recyclable' does not mean, however, '100% recycled': remelting of cullet is possible only after an expensive sorting step, necessary to separate glass from other materials [9]. Sorting in the case of common soda-lime glass is typically realized by the crushing of containers, followed by separation of glass fragments (destined to remelting) from pieces attributable to other materials; the crushing generates big amounts of fine particles, <100 μm, with glass as dominant component, but undoubtedly enriched in heterogeneities, and still disposed in landfills [10]. In some cases, remelting is hindered by specific technical difficulties, such as volatilization of fluorine from F-containing opal glass [11]. Discarded fractions of glass cullet, of any composition, represent a real form of industrial waste ('waste glasses'). Discarded material, of no value or even of 'negative' value (i.e. implying costs for transportation and disposal in landfills), is used as feedstock for products generating sufficient revenues to compensate the whole recovery process [10]. Highly porous cellular glasses, also known as 'glass foams', provide an interesting opportunity for upcycling of waste glass [12,13].

To consistently quantify the overall environmental impacts associated to products, multi-criteria assessment methods and life cycle approaches are recommended by scientists, to avoid the risk of burdens shifting [14]. Life Cycle Assessment (LCA) is known as the most robust methodology to evaluate the environmental performance of products, processes and technologies, thanks to 'cradle to grave' perspective and multi-criteria quantification of environmental impacts [15]. Standardised by International Organization for Standardization (ISO), LCA supports the sustainable consumption and production patterns and helps develop environmental innovations in the circular economy framework [16]. In the last 20 years many studies have used LCA to understand the environmental impacts of new products and processes, as well as to identify the roots of varying hazards and allows decision-makers to improve the environmental performance of waste management practices [17]. Moreover, within circular economy projects, even if 'life cycle indicators' and 'circularity measures' do not coincide, LCA may be applied to identify the most promising circular economy strategies and options [16]. In fact, a large amount of papers testify to the usefulness of LCA in R&D and eco-design, to verify the environmental preferability of new materials and products [18], to optimize new processes or technologies, and to identify potential supply chain hotspots that contribute to the overall environmental impacts of innovation [19]. The application of LCA to the early stage development of a process is recommended by scientists [20]: determining where improvements can be made whilst a process is still at the laboratory stage can be key to unlocking the environmental improvement potential. The effectiveness of LCA in predicting the environmental impacts of new technologies or processes means that the use of this methodology in the design phase and at the lab-scale is also encouraged through numerous policies and legislation, such as the European Directives (e.g. EC 2003 [21]; EC 2006 [22]; EC 2009 [23]).

Innovative applications of solid waste in building insulation materials are of great significance because energy shortages and environmental pollution are two global problems that urgently need to be solved [24]. LCA can give an insight on the environmental performance and the impacts related to constructions [25]. The introduction of insulation materials improves energy performance of buildings by reducing the heat losses [26,27]. To further increase the environmental benefits, the installation of new insulation products made with recycled materials is recommended [25].

In the last decade a huge number of papers was published in which the environmental preferability of new insulation materials was assessed through the LCA methodology (e.g. Refs. [28,29]), also including renewable materials or secondary raw materials derived by waste recycling (e.g. Refs. [30,31]). However, only few papers concern the impacts of glass foams made from waste glass. In particular, Cozzarini et al. [32] highlighted that the greatest contributions to the impacts rely on the chemicals and on the energy demand, higher than that required by more common (although less durable) polymer-based insulating materials. Blengini et al. [33] specifically evidenced that an improvement in the sustainability would be achieved by substitution of silicon carbide (SiC) as foaming agent. The previously mentioned 'inorganic gel casting' method [34] effectively goes in this direction: the usual chemicals are avoided by a complete change in the manufacturing approach. Foaming *during* sintering is replaced by sintering *after* foaming of glass suspensions, by intensive mechanical stirring.

The main objective of this study is to analyze through the LCA methodology the impacts of glass foams manufactured according to the new method carried out in laboratory scale at University of Padova. The analysis focuses on finding the processing steps mostly contributing to the total impact, to better understand the strengths and weaknesses of the technology form a life cycle point of view.

1.1. Glass foam manufacturing

Glass foams probably represent the most appreciable expression of viscous flow sintering of glass, realized at much lower temperatures (850–1000 °C) than glass melting (>1400 °C). The cellular structure is determined by gas evolution, within a 'pyroplastic mass' formed as an effect of the same glass sintering, operated by selected additives (foaming agents), undergoing decomposition or oxidation reactions [12]. Typical decomposition-driven foaming agents are represented by carbonates and sulphates, whereas oxidation reactions apply to carbon (carbon black, graphite), organic compounds or SiC, causing CO/CO_2 evolution. The adoption of a sintering approach, at moderately low temperatures (850–900 °C), allows for the introduction of variously sorted glass powders, mixed with foaming agents, also in powder form.

A homogenous foaming is a fundamental requirement in cellular glasses. To achieve this, carbon-containing foaming agents are typically assisted by additives (such as sulphates), intended to provide oxygen besides that supplied by the atmosphere [35,36]. In any case, a delicate balance must be established between viscous flow and gas evolution: as pointed out by Petersen et al. [37], specifically describing a 'viscosity window', the firing temperature should be high enough to activate the foaming agent (and the oxygen supplier), without causing a viscosity decrease below a certain threshold, to prevent the collapse of gas bubbles. If the starting feedstock is glass powders with limited composition variations, this is rather straightforward; on the contrary, if a mixture of different glasses is adopted, the same processing temperature determines different level of viscosity in the softened mass, resulting in inhomogeneous foams, as illustrated by Fig. 1.

An alternative process was introduced to overcome the above-mentioned issues. According to alkali activation of 'inorganic gel casting' [11,37] glass powders form pseudoplastic slurries, by progressive gelation after being suspended in alkaline aqueous solution. For common soda-lime glass, an alkaline attack at moderate molarity (concentration of 2.5–3 M NaOH or KOH) determines the formation of calcium silicate hydrated (C–S–H) gels at the surface of glass particles. Due to interactions between surface gels, suspensions pass from a lower apparent viscosity state (upon intensive mechanical stirring) to a higher apparent viscosity state (when stirring stops), preventing any collapse of trapped air bubbles. Air bubbles are further stabilized by the addition of surfactants. A cellular structure is already available just after drying (Fig. 2, left). A thermal treatment (at only 700 °C), after drying and demolding of hardened suspensions, is later applied for the joining of glass particles, with some additional gas release from decomposition of gels (Fig. 2, right).

1.2. LCA of glass foam

The LCA methodology consists of 4 phases: the goal and scope definition, inventory analysis, impact assessment and interpretation [14]. Two international standards support practitioners to conduct comprehensive LCA studies: the ISO 14040 [38] contains principles and fundaments to consistently apply the LCA methodology, and the ISO 14044 [39] establishes guidelines and requirements to correctly carry out each step of LCA. LCA is often used to quantify the environmental profile of construction materials production and assess buildings energetic performance: in these cases, the standard EN 15804, which contains specific indications for applying LCA to the construction sector, must also be used [40].

In a circular economy perspective, the focus has been on the recycling of waste, like post-consumer PET bottles, as secondary raw materials to manufacture new construction materials [41]. The practice, in the construction sector, for allocating emission of recyclable products from recycled inputs is to use the 'cut-off' or 'input-oriented' method; therefore, the benefits of the use of recycled material for production is rewarded rather than the product recyclability [40]. The reason for this choice is the long life of a building which makes future predictions of the product recycling unreliable [42]. Given the insulation function of glass foams different studies of insulation materials are analized. The LCA of building materials can include the entire life of the builing or only of the materials used; both 'cradle to gate' and 'cradle to grave' studies can be done [43]. It is also advised to use the LCA at the design level to lower the impacts by optiminizng the choice of materials used [44].

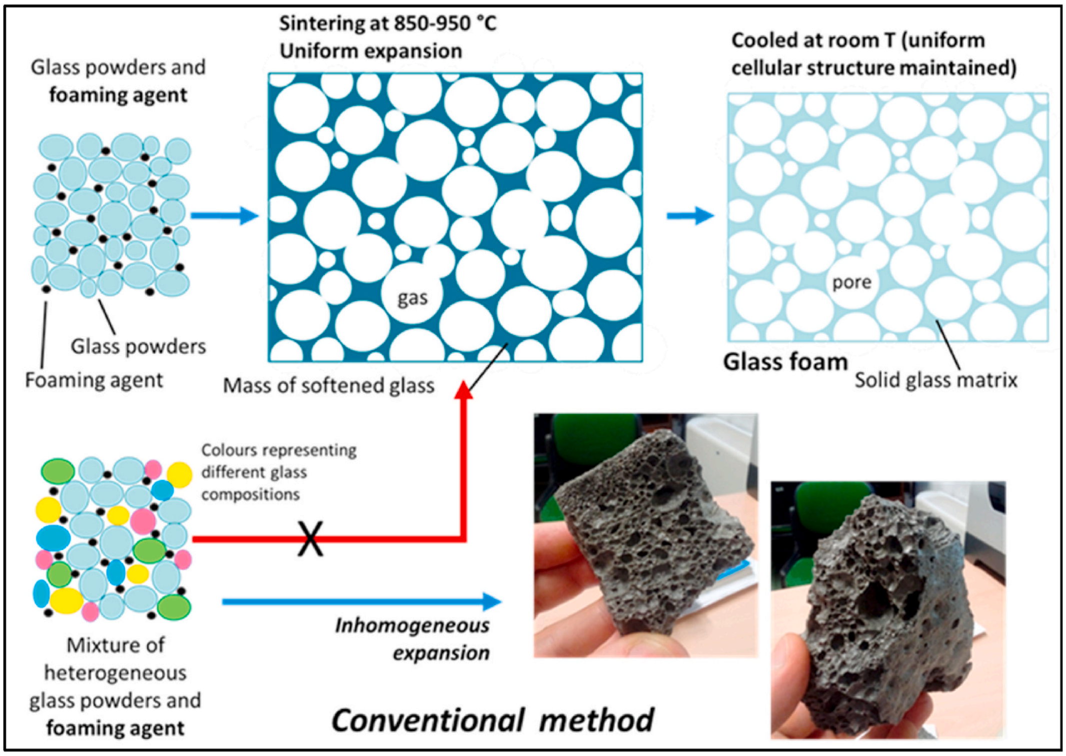

Fig. 1. Scheme of conventional foaming, named 'foaming during sintering'.

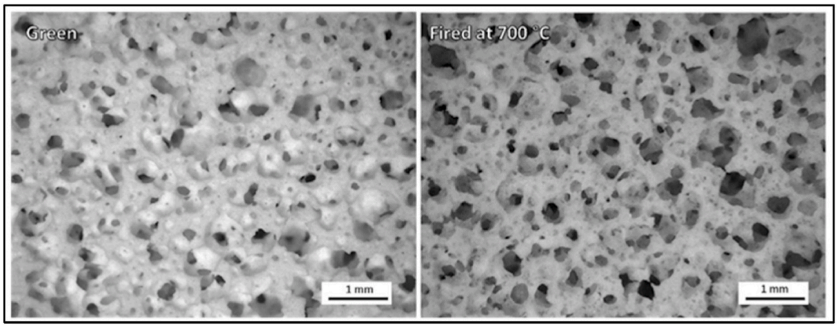

Fig. 2. Example of glass foam from inorganic gel casting, based on cullet of F-containing opal glass. Left image: after alkali activation, room temperature foaming and drying. Right image: after firing.

Within the international scientific literature, the glass foam production from waste glass upcycling is already analyzed. The impacts of the glass foams are assessed in some LCA studies in which different glass foam production methods are compared among them and with other insulation's materials. Even if the same functional unit (FU), that quantifies the product system performance [38], is needed to be able to compare the different materials through an LCA, however, different FU are chosen by scientists to quantify the environmental profile of glass foam production from waste glass. Some papers use the area or weight to have a specific thermal insulation as FU; other papers adopt product dimensions or other characteristics of materials as FU [45]; moreover, to compare environmental performances of different glass foams, 1 kg of glass foams from waste glass is also adopted [46].

From the literature review, other relevant information can be summarized. The production phase is always analyzed in the LCA studies, since it is the main difference from the other insulation material. The major impact of the glass foam life is the energy consumption from the machineries; choosing renewable energy sources rather than fossil one can improve the environmental performance of the material. On the contrary, other life cycle stages of glass foam are rarely included in previous LCA studies. The downstream phase related to the transportation of glass waste from waste production site to the glass foam production process is frequently not considered, even if its impacts can be non-negligible and can outweigh the benefits of the recycled material [36]. The upstream phase related to the distribution and installation of materials within the buildings, and their end of life are often excluded by the life cycle analysis; otherwise, the use phase is generally not considered since environmental benefits of the energy saved from the glass foam insulation, are comparable to those of other materials [35].

From the literature overview, further research questions arise. The LCA of glass foam from waste glass upcycling should include both the downstream and upstream phases, focusing the attention on the transportation and disposal, to assess their importance in the environmental profile of glass foam life cycle. The energy consumption contribution should also be further investigated.

2. Materials and methods

2.1. Details about the glass foam production in lab scale

According to the methodology proposed by Rincón et al. [34], the process comprises the following stages:

i) collection of waste (soda-lime) container glass already in form of fine particles (<75 μm), corresponding to the fraction of soda-lime cullet that remains practically unusable, after color selection and removal of metallic and polymeric residues, due to the presence of ceramic contaminations;
ii) alkaline attack in 2.5 M KOH aqueous solution, under magnetic stirring (500 rpm), for 3 h, at room temperature;
iii) preliminary gelation by heating of suspensions, in closed plastic molds, at 75 °C, for 2 h;
iv) addition of 4 wt% (compared to glass content) surfactant (polyoxyethylene octyl phenyl ether – $C_{14}H_{22}O(C_2H_4O)_n$, n = 9–10);
v) application of vigorous stirring (2000 rpm) for 10 min; vi) 'curing' (completion of gelation and drying) at 75 °C, for 24 h; vi) demolding and vii) firing at 700 °C, for 1 h, after heating at 10 °C/min.

2.2. Details about the LCA study of glass foam

2.2.1. Goal and scope

The goal of the LCA study is the evaluation of the potential environmental impacts of glass foams made from crush soda lime glass, recycled form waste glass collection containers, by alkali activation and gel casting at a laboratory level. The FU assumed is1 kg of glass foam, produced by alkali activation and gel casting in a laboratory setting [46]. The system boundaries include the waste glass transportation from the recycling facility to the laboratory, the production, the use phase, and the end of life of the product. The input glass is assumed to come from the waste collection and to consequently determine an advantage from avoided production of virgin glass and avoided waste landfilling. The recyclability at the end of life, on the contrary, is not considered coherently with the international standard recommendations [40]. The primary material derives by waste collection and glass waste selection activities made by an Italian company located in Biella, in northern Italy. The glass waste is the input to produce glass foams in a laboratory at Padova University, in northern Italy. In this analysis it is assumed that the production process does not create any waste and all the material used is translated in the final product. The use phase of glass foam is hypothesized in a new building located in Germany, and the end of life is assumed near the location of building.

The life of the glass foams is modeled as in Fig. 3. It is divided in three main phases including the input materials and production ('glass foam production'), the transportation and installation ('glass foam use phase'), and the final disposal ('glass foam end of life'). The production phase is divided in 6 steps, to analyze the contributions of each process: alkali activation, gelation, addition of surfactant, foaming, currying and drying, firing.

2.2.2. *Life cycle inventory analysis*

2.2.2.1. Assumptions and formulas. The material inputs for the glass foam production are assumed from the paper from Rincón et al. [34]. Average quantities for the transportations are also supposed. Other secondary data was retrieved from the Ecoinvent 3 database. The entries selected on the database are chosen at system level to fasten the computation. The transformation entries are chosen when the distance from the productor is known, while the market ones when the location is unknown.

The residual fine fraction of the glass waste is collected from the recycling facility and transported to the laboratory where it is used to produce the glass foams; the fine powders, remained unusable due to the contaminants, is used as received [34,37]. All the chemicals needed in the productions processes are assumed to be bought and transported on a 40ton truck for 500 km.

Mechanical stirrers are used several times in the production and their contribution is given by the electrical consumption of the machinery; to calculate it in different conditions, a linear proportionality is assumed between power (P) and angular velocity (ω), ruled by torque (τ), as in 1, valid up to the maximum values, as in 2:

$$P = \tau * \omega \tag{1}$$

$$P_{max} = \tau * \omega_{max} \tag{2}$$

From which we infer, as in 3:

$$P = P_{max} * \frac{\omega}{\omega_{max}} \tag{3}$$

To find the electrical consumption, the power is then multiplied by the time in which the machinery is used.

The laboratory oven and the muffle used for the gelation, curing, and firing of the material can reach a higher temperature compared to the one needed for the processes to make glass foams. To calculate the power consumption at lower temperature, a linear proportionality, between power (P) and temperature (T), ruled by thermal resistance (R_t) is assumed again, as in 4 and 5:

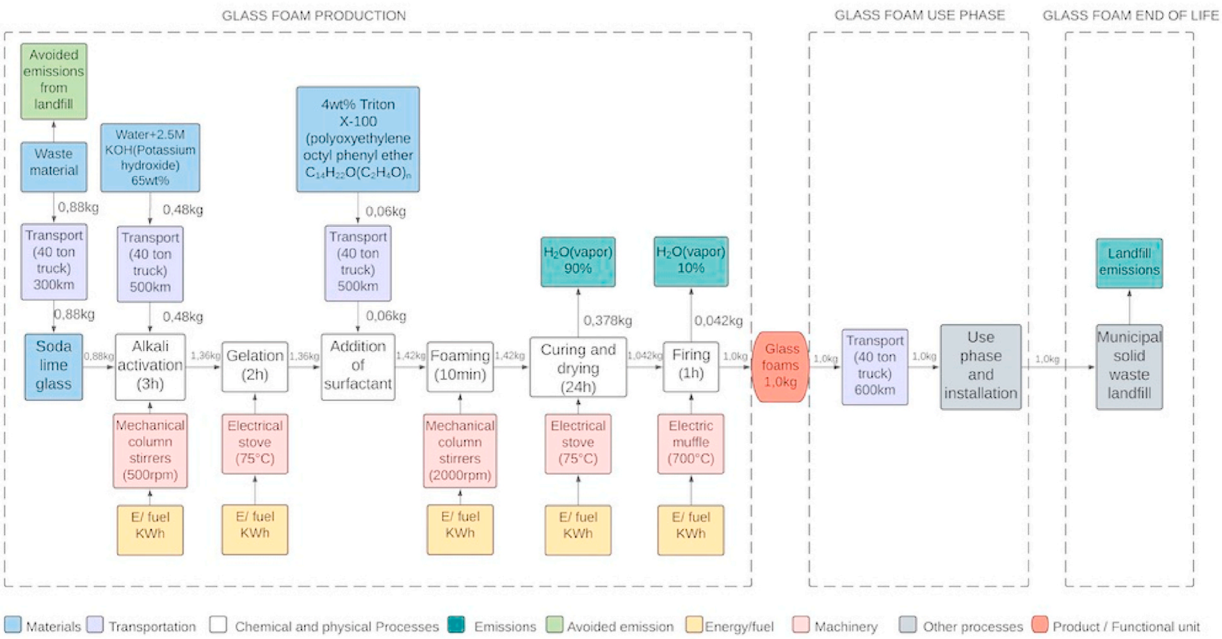

Fig. 3. Glass foam life cycle model.

$$P_{max} = \frac{(T_{max} - T_A)}{R_t} \rightarrow R_t = \frac{(T_{max} - T_A)}{P_{max}} \quad (4)$$

$$P = \frac{(T - T_A)}{R_t} = P_{max}\frac{(T - T_A)}{(T_{max} - T_A)} \quad (5)$$

where T_A and T_{max} are ambient and maximum temperature, respectively.

If included, the warming up time and the temperature holding power of the machines are used; the total electrical consumption is then estimated by multiplying the power, at the needed temperature, and the heating time and then adding them to the holding power for the residual time required. For all electrical machinery, the electricity mix at low voltage for Italy is selected for the calculation of the potential impacts.

After its production, the glass foam material is transported to the installation location in which it will be used, and then, at the end of the use phase, it is disposed in the landfill. Installation and use are supposed without any environmental effects because during these phases there are no inputs and outputs of materials, energies, emissions or waste (in line with [35]).

2.2.2.2. Input-output analysis. Soda lime glass: The input material is the glass fraction from the waste glass container, from separate collection, that cannot be used for the conventional recycling. To produce 1 kg of product 0.88 kg of soda lime glass are needed; since the material is delivered already as a fine power there is no need for further processing. As the material used was destined to be disposed in a landfill due to its non-recyclability in traditional ways, the product will have some environmental gain given by the landfill avoidance; other gains are given using recycled materials due to the avoidance of the production of virgin materials. These advantages are considered by selecting the cullet made of waste glass from the Ecoinvent 3 database. The waste material is considered to be transported on a 40ton truck for 300 km, which is the distance between the recycling company (located in Biella, Italy) and the laboratory in which the production takes place (University of Padova, Padova, Italy). The input for the transportation process is calculated by multiplying the distance by the weight of the materials in tons and it is equal to 0.264 tkm.

Alkali activation: The first process of the product manufacturing is the alkali activation. According to Rincón et al. [34] to obtain a good quality glass foam, a 65 wt% of fine powder soda-lime glass is mixed with the aqueous solution. To produce 1 kg of glass foam from the 0.88 kg of waste glass, a 0.48 kg of water and 2.5 M KOH has to be added; this means that the potassium hydroxide needed is 0.006 kg. The potassium hydroxide is transported for 500 km while the water transportation is not included. The calculations for the transportation of the material are the same for the previous process; it results in 0.03 tkm. The electric consumption of the mechanical stirrer is calculated at 500 rpm using the machinery characteristics; the nominal power of the machinery from the technical sheet found at 2500 rpm is 60 W. The torque estimated is 0.23 Nm and, when used in F.1, the P (500 rpm) is equal to 12 W; if used for 3 h the energy consumption is 36 Wh.

Gelation: The achieved suspension is then cast in molds and treated in an electric laboratory oven [34]; the molds are not affected by the process and can be reused so they are not included in the LCA study. No additional materials are added during this process so its contribution to the total impacts is given solely by the electricity consumption. The oven used has a maximum temperature of 250 °C with a nominal power of 1000 W. From 3 to 4 equations, the maximum power required to heat the oven at 75 °C, considering an ambient temperature of 20 °C, for is 239.13 W. The time to reach the temperature required for the gelation is 23 min (0.38 h) according to the technical sheet of the oven, while the power needed to hold the temperature inside the oven is 342 W. The estimated total consumption of the oven at 75° for 2 h needed for the gelation is 161.1 Wh. The total power is presumed to be divided by 4 considering that the oven has a volume much higher than the material so it is probable that the oven will be used for other materials as well.

Addition of surfactant: After the gelation, 4 wt% of Triton X-100 is added to the obtained gel; to produce 1 kg of glass of foam it is necessary to add 0.06 kg of surfactant. Data on the Triton X-100 is not present on the available databases for the study; however its production was assumed as similar to that of ethoxylated alcohol (AE11) non-ionic surfactant, which is available in the database. The material transport is selected with a value of 0.02836 km.

Foaming: After the addition of surfactant, the materials are stirred together at 2000 rpm for 10min (0.17 h) with the machinery; to calculate the energy consumption of the mechanical mixer at the required speed, the same machinery characteristics and method are used. The Power at 2000 rpm found with 1 is equal to 48 W; if used for 0.17 h the energy consumption is 8 Wh.

Curing and drying: The obtained foam is then cured for 24 h at 75 °C in the same oven as the gelation process. The same calculations and assumptions are done and therefore the same characteristics, as the power at the required temperature and the holding power, are obtained; the temperature holding power is although multiplied for the 24 h minus the warming up time. As in the gelation process the power is divided by 4 for the higher volume of the oven. According to the method previously described, the estimated electric consumption is equal to 2042.14 Wh. In this procedure, the water previously added is partially evaporated; it is assumed that 90% of the water evaporate in the drying phase. The water vapor leaves the system boundary in this phase as an emission to air.

Firing: To obtain the final product, the cured material has to be fired at 700 °C in a muffle for 1 h. The selected equipment has a nominal power of 2400 W at the maximum temperature of 1100 °C; the warmup time of 0.78 h and the temperature hold power of 790 W are also included in the technical sheet of the machinery. The estimated power of the muffle at 700 °C is 1511.11 W and the total energy consumption is 1354.8 Wh. The remaining water present in the material, in this phase, evaporates; the water vapor leaves as an emission to air.

Glass foam use phase: Due to the lack of data on the on the processes for the installation and the use of the product due to its laboratory nature, no emissions or materials are assumed to be included in this phase. The only process supposed is the transportation of the product to the installation location. The distance is assumed to be 600 km; the input value is calculated and assumed as the previous transportation processes and is equal to 0.6 tkm.

Glass foam end of life: As previously mentioned, due to the long life of the buildings, the final recyclability of building materials should not be accounted. The glass foam product reaches the end of life when the building is demolished, and it is disposed. Since the glass foam does not degrade or changes its characteristics over time it can be considered as an inert waste. For this reason, it is assumed to dispose the product in the municipal solid waste landfill; this is considered as a precautionary hypothesis, since possible advantages from further recycling have to be neglected.

3. Results

The results of the life cycle impact assessment are reported in Fig. 4; characterization results are in Fig. 4A, whereas normalized results are in Fig. 4B. The SimaPro software is used to implement the model and the ReCiPe 2016 method is used at midpoint level for the impact assessment to transform the input data into environmental impacts.

From the characterization of results by SimaPro simulation (Fig. 4A), the production phase has a great influence on the overall impacts of the glass foam life. Indeed, the production is the highest contributor in half of the categories, but it also has some environmental gains, due to the recycled material used, on the impact categories of the freshwater and marine eutrophication, land use and minerals resource scarcity. A great contribution to the environmental profile is given by the use phase, due to the transportation of final product from production site to installation site. The end of life is relevant only in 4 impact categories, related to marine eutrophication, freshwater and marine ecotoxicity, and human non-carcinogenic toxicity. From the normalization of results obtained by the SimaPro simulation (Fig. 4B), the impact of product life relies mostly on four categories, consisting of marine and freshwater ecotoxicity and human carcinogenic and non-carcinogenic. The main relevant impact category from the normalized results, the human carcinogenic, testifies as greater contribution on the environmental impact the transportation of foam glass from the lab to the use in building installation, while end of life in landfill is the highest contributor in the other categories.

Due to the high contribution of the production processes in the characterization results, the contribution of the singular processes

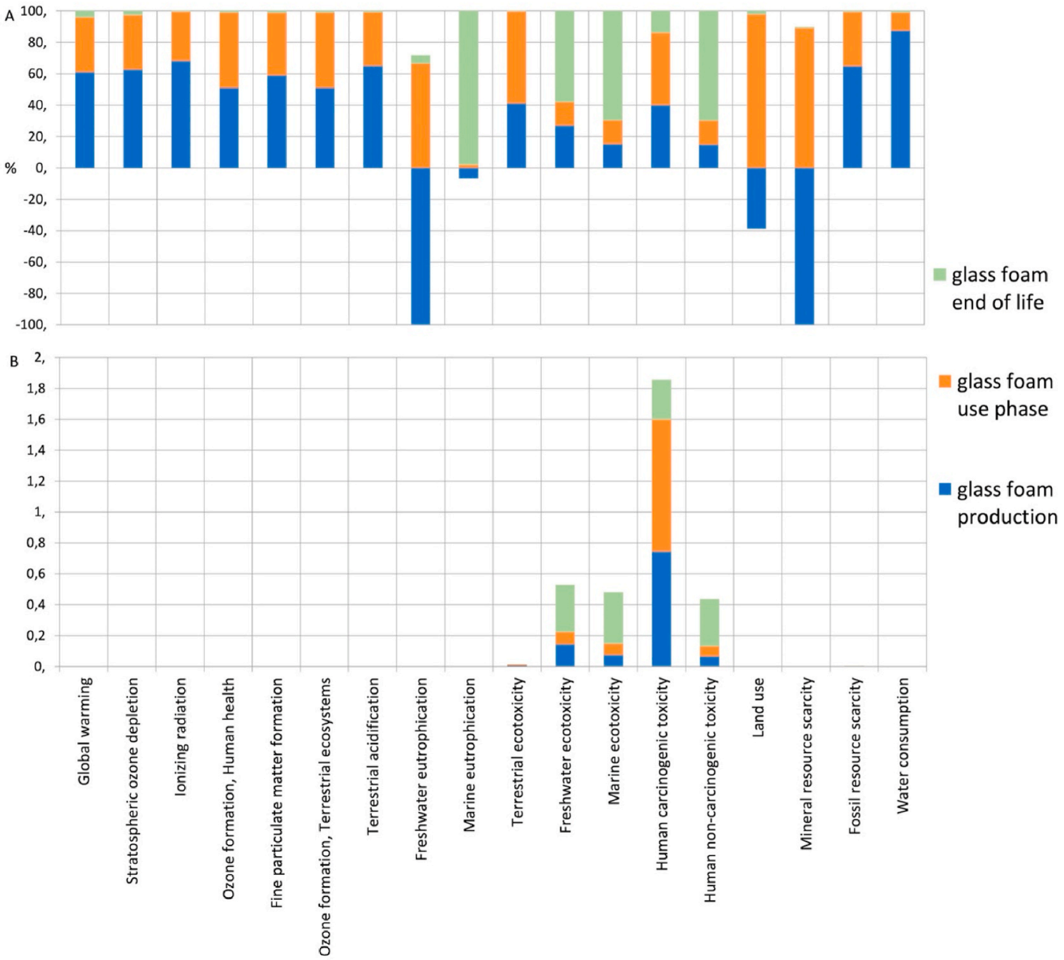

Fig. 4. Characterization (A) and Normalization (B) results of life cycle impact assessment of glass foam.

on the production are analyzed by the gravity analysis, coherently with the requirements of ISO 14044 [39]: Fig. 5 reports the categorization results obtained by the SimaPro simulation in the hotspot analysis. The greater contribution is given by the curing and firing processes, given the high-power usage. During the curing process, the drying of the material at 75 °C for 24 h cause between 30 and 40% of the production impact in almost all impact categories; for the firing process, the sintering at 700 °C accounts for approximately 20–30% of the impact. In general, the electricity usage contributes for more than half of the total production impact; exceptions are the categories of marine eutrophication and mineral resources scarcity. Compared to the electrical consumption, the chemicals added to the soda lime glass contribute to the overall impact to a limited extent. While the KOH has a minor impact, the Triton X-100, used as surfactant, has not negligible impact, especially on the marine eutrophication category. As seen from the whole life cycle impact assessment results, the input waste glass has a negative impact in the environmental profile, due to the avoided production of new virgin glass and its avoided landfilling, on a few categories. If normalized, results of production steps mostly affect the human non-carcinogenic toxicity impact category with the major contributor being the curing and firing processes, while a negative contribution is given by the recycled material.

4. Discussion

The distance from the recycling facility to the laboratory and the distance from the laboratory to the installation in the use phase represent the most significant factors within the life cycle impact assessment, then further investigations are needed to better understand potential benefits in the environmental profile related to minor distances between waste glass collection, glass foam production and glass foam use. The sensitivity analysis of life cycle impact assessment should prove the influence of the recycling facility distance on the benefits of the recycled material and of the transportation of the final product on the total impacts.

Two improvement scenarios are compared. In the first one (scenario A) the recycled material transportation distance is reduced from 300 km to 100 km, thinking at a glass foam production facility closer to a glass recycling plant. In the second scenario (scenario B), the product transportation distance value is decreased from 600 km to 100 km, assuming that the glass foam would be installed in the same region in which the laboratory produces it.

The sensitivity analysis results (Fig. 6, green columns) prove that lowering the transportation distance decrease the overall impacts in all the categories. Decreasing the installation location distance causes a conspicuous difference in most of the categories (Fig. 6, orange orange). In the scenario A although the impact decrease, the differences are not as noticeable as in the scenario B due to the lower initial distance and the lower quantity of material to be transported.

The major contribution of the production phase is given by the electricity consumed by the machinery, such as the oven (for drying) and the furnace (for sintering). Since the laboratory is located in Italy, the national energy mix is used in the base scenario. To see the influence of the location choice, the results are compared, through a sensitivity analysis, with a scenario C in which the electricity comes from the average European energy mix (Fig. 7). While for the previous parameters the results were expected, for the change of energy mix the effect were not predictable given the many factors included in the electricity mixes input; different mixes represent a different percentage and kinds of renewable and non-renewable energy sources affecting differently on different impact categories. From the results (Fig. 7) it appears that the impacts are sensitive to a change in the country energy mix, although there is no evident direct improvement with one mix over the other. It is possible that some country's energy mix, preferably with high percentages of

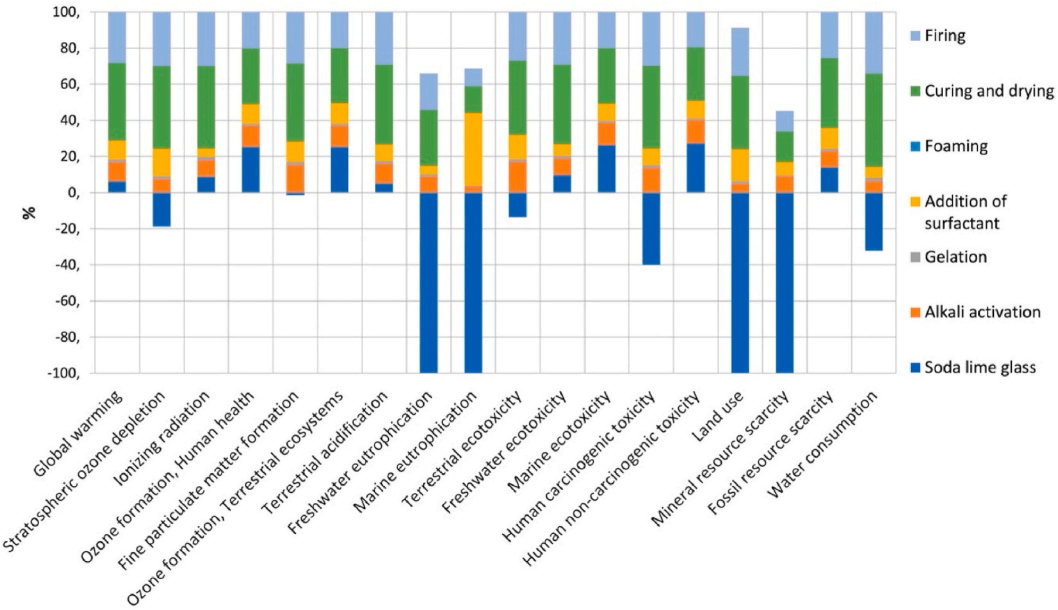

Fig. 5. Characterization of life cycle impact assessment results related to the production process.

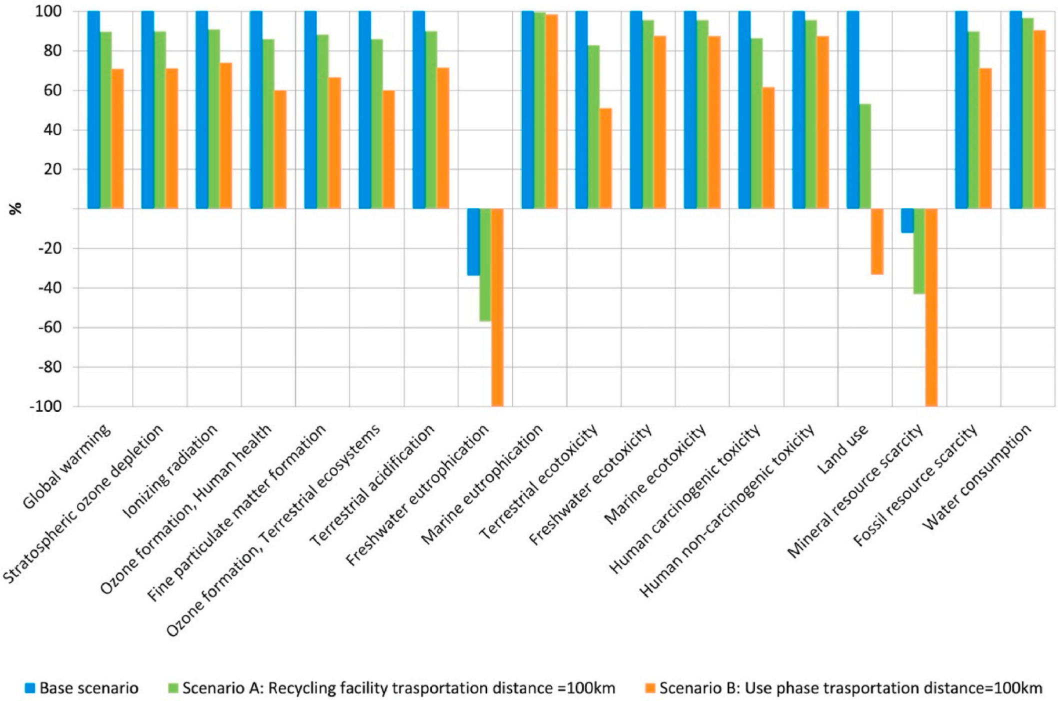

Fig. 6. Sensitivity analysis of LCA results related to the base scenario (blue bars) changing the transport distance from the recycling facility to the laboratory location (green bars) and from the laboratory to the installation location (orange bars).

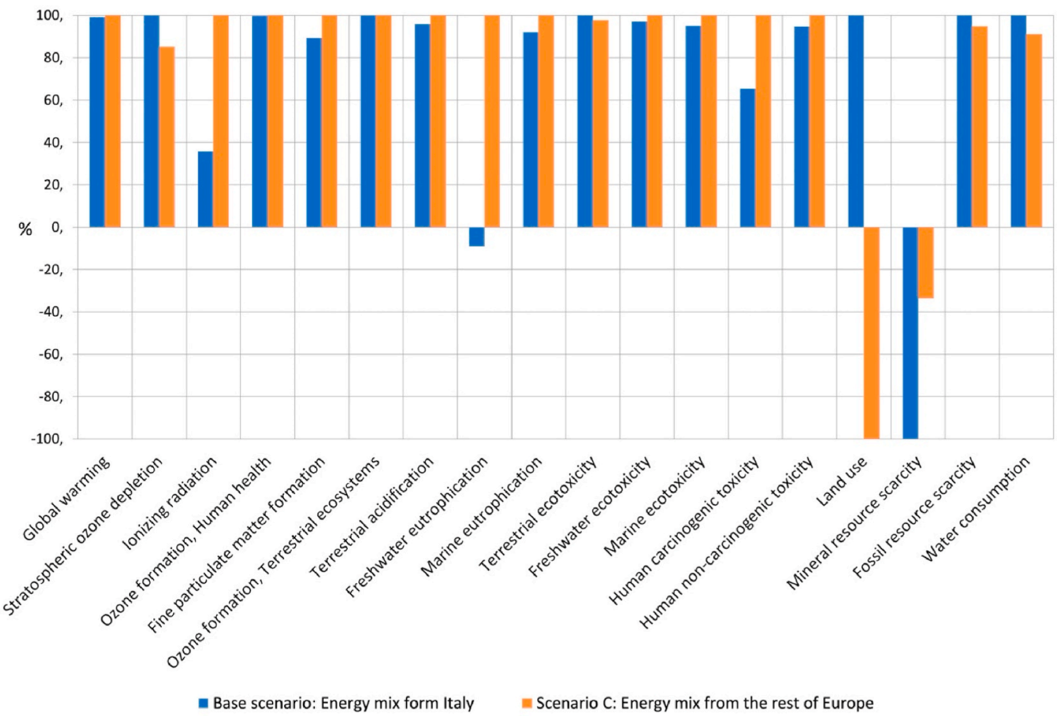

Fig. 7. Sensitivity analysis of LCA results related to the base scenario (blue bars) changing the energy mix (orange bars).

renewable sources, would have a more favorable overall impact giving the material a more sustainable production.

The study of laboratory conditions, instead of industrial conditions, is obviously limiting, and in particular other potential benefits available at industrial scale are not considered in this lab scale. For example, in case of large-scale operations, a proper 'thermal engineering' could be considered, e.g. involving recovery of heat from the sintering step in the drying step. In any case, the 'ex-ante' LCA study with reference to the laboratory conditions gives important stimuli to optimize the alkali activation process, and to introduce other innovative solutions before the industrial exploitation.

The improvements evidenced by the sensitivity analyses, anyway, will hardly compensate what remains challenging. The replacement of the 'foaming during sintering' method for glass foams (conventional method, with foaming agents added to glass powders) with the 'foaming after sintering' (at lower temperatures) method does not minimize energy impacts, in the production, since drying is not negligible. To consistently reduce the environmental impacts of the glass foam, more attention should be given to surfactants, of not negligible impact, despite the limited quantity. Future investigations will undoubtedly involve the selection of biodegradable surfactants, from renewable sources.

A remarkable saving in the production phase is envisaged by the removal of the sintering step, according to the manufacturing of foams directly useable after gelation. This is possible in hypothesis of stronger and more durable mutual bonding of alkali activated glass powders, which could be determined by replacing C–S–H compounds with hydrated Na- and Ca-based alumino-silicates. In this case, attention would pass to selecting alumina-rich additives which, consistently with sustainability goal, should be waste-derived (a possible example is provided by volcanic ash [47]). The limited strength-to-density of 'cold-consolidated' foams, compared to that of glass foams, remains as an open issue.

5. Conclusions

The environmental profile of glass foam made from recycled crush soda lime glass by alkali activation and gel casting at laboratory level is assessed through the LCA methodology, to underline the environmental hotspots in the glass foam life cycle. The results show that the most impacting phases are the production and the transportation from waste collection to glass foam production, and from glass foam production to the use site. The end of life in the landfill only have relevant impact on few categories. The contribution of production processes is further analyzed, and the gravity analysis shows that, accordingly with previous papers, the major contribution of the production impact is given by the electricity consumption which accounts for more than half of the impact. According to the assumptions made in the inventory phase of LCA study, the higher contributors are the curing phase, due to its long duration, and the firing process for the high temperature needed. Among the materials added, the surfactant applied has the highest impact due to its production. Although there are noticeable benefits in using recycled materials instead of virgin one, they are reduced by their transportation during the life cycle stages. It is proven by sensitivity analyses that reducing the distance decreased the impact in every category while changing the energy mix would not directly bring an improvement to the product performance.

Given the impact of the energy and surfactant, further research is needed to improve the process and compare it with other methods. In particular, a possible strategy could be represented by the complete removal of the sintering stage, e.g., in case of development of particularly chemically and mechanically resistant gels in green foams.

Author contribution statement

Anna Mazzi: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Michela Sciarrone: Performed the experiments; Wrote the paper.
Enrico Bernardo: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

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.

Acknowledgements

This research was funded by the University of Padova (Dept. of Industrial Engineering), in the framework of the "SusPIRe" (Sustainable porous ceramics from inorganic residues, BIRD202134).

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