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Evaluating environmental impacts of geopolymer and straw-based wood wool cement boards

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ABSTRACT

This study assesses the environmental and performance implications of utilizing industrial and agricultural by-products as alternative raw materials in the manufacturing of wood wool cement boards (WWCB). In this context, fly-ash based geopolymer replaces OPC, and straws replace spruce wood wool. Both economic and no allocation methods are applied to these by-products to assess their life cycle impacts according to EN 15804 +A2. The findings highlight the environmental benefits of replacing OPC with geopolymer in terms of global warming potential, although the impact on other environmental indicators is less certain. However, substituting straws for wood wool in the production of straw geopolymer boards (SGB) results in poor environmental and performance outcomes, diminishing its viability as a solution. Notably, the treatment of straws does not substantially enhance overall performance and leads to a higher environmental burden. Furthermore, the study recommends adopting a consistent by-product allocation method to ensure accurate reporting of environmental impacts across different industries.

1. Introduction

Wood wool cement boards (WWCB), composed of wood wool fibres bonded with ordinary Portland cement (OPC), are widely used for acoustic and thermal insulation in buildings [1–3] [1–3]. To reduce the high embodied carbon associated with OPC manufacturing, geopolymers have emerged as alternative binders, enabling the production of wood wool geopolymer boards (WWGB). Previous research [4] has demonstrated the feasibility of using geopolymers as a viable alternative to OPC in WWGB production, providing insights into manufacturing methods, design parameters, and performance. Additionally, straws, by-products of crop production, have been identified as potential non-wood fibres for creating straw-geopolymer composites [5–9], suggesting the feasibility of replacing commercially produced wood wool in the production of straw geopolymer boards (SGB).

However, there is a research gap in the actual quantification of the environmental benefit and a comprehensive life cycle assessment (LCA) on these alternative raw material substitutions. To validate the environmental advantages of alternative raw materials, LCA systematically assesses various potential environmental impacts. Previous LCA studies on geopolymers [10–12] indicate that alkali activators and heat curing are dominant factors affecting environmental impacts. Additionally, the allocation method for industrial and agricultural by-products, including fly ash (FA), ground granulated blast furnace slag (GGBFS), and straws, requires detailed consideration.

FA and GGBFS could be categorized as waste or by-products of industrial processes. According to the European Waste Framework Directive [13], both FA and GGBFS are defined as by-products rather than end-of-waste. This classification is reinforced in the Netherlands, where both FA and steel slags are deemed by-products, as outlined in legal opinions [14,15] and case law [16]. Despite these clarifications, technical issues such as allocation methods remain undefined, and industry actions further introduce complexity. CEMBUREAU (European Cement Association) considers both GGBFS and FA as by-products of steel and electricity production, respectively, applying economic allocation, as reflected in their official environmental product declaration (EPD) for CEM II and CEM III [17,18]. Conversely, GCCA (Global Cement and Concrete Association) and PCA (Portland Cement Association) recommend no allocation when utilizing GGBFS and FA in cement production, considering them as waste from previous life cycles [19,20]. Meanwhile, the World Steel Association [21] advocates the system expansion method for GGBFS, or an alternative physical partitioning method proposed by Eurofer (European Steel Association) [22], both resulting in higher greenhouse gas (GHG) emissions for BFS compared to

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economic and no allocation methods [22].

LCA studies [11,23] reveal similar concerns, where different allocation scenarios significantly impact the overall life cycle performance of FA or GGBFS-based geopolymer composite. Applying mass allocation to FA or GGBFS may result in more than double the global warming potential (GWP) in geopolymer compared to OPC, while economic allocation could yield a similar GWP to OPC [11], potentially disincentivizing the replacement of OPC with conventional industrial by-product. Conversely, applying no allocation methods could lead to under-reporting the overall environmental footprint of the products.

Wood wools are commercially produced from wood logs harvested from forest plantations, typically spruce woods. While wood is considered a renewable biomass resource, the environmental impacts from its harvesting must be accounted for, which are closely related to forest management and supply chain practices [24–26]. On the other hand, straws are abundant, sustainable, and cost-effective sources of low-embodied carbon raw materials [27]. Agricultural by-products such as straws are excluded from the European Waste Framework [13]. This exclusion aligns with the European Renewable Energy Directive [28], which classifies straw as agricultural waste and residue, primarily promoting renewable biofuels. Proposals for fair allocation between the agriculture sector and other industries utilizing agricultural by-products as raw material are available, based on mass, energy, or economic values [29].

To quantify the raw material and manufacturing requirements for LCA, WWGB production from the study [4] is referenced, while SGB are manufactured following the same WWGB fabrication procedure. Two commonly available straw types, wheat and barley straws, are selected for SGB production based on their status as the top two grain crops produced in the Netherlands. Both straws possess distinct physical properties and chemical compositions, with barley straw having a wider and fuller stalk than wheat straw, along with higher wax and lignin contents [30]. However, unprocessed straws may require additional treatment, such as alkali treatment, to improve adhesion between fibres and binders by decreasing fibre hydrophobicity and roughness [31]. In contrast, wood wools are specifically produced into thin flat strains for optimized production of WWCB, where additional treatment is not necessary. The influence of fibre selection and treatment, both physically and environmentally, requires investigation.

This study aims to investigate the environmental performance of insulation boards using alternative raw materials. Straws as alternative fibres for wood wool, and geopolymer as an alternative for OPC, are explored as substitutes in WWCB production. To ensure the feasibility of these substitutions, SGBs are fabricated, and their physical characteristics (physical, mechanical, thermal, and hygric) are compared against WWGB and WWCB. The life cycle assessment from the perspective of material replacement, allocation method, and design parameters are investigated and discussed. The findings aim to address research gaps by quantifying the environmental benefits of alternative raw material substitutions in insulation board production.

2. Material and Methodology

2.1. Raw Material

Wheat and barley straws, obtained locally from Strobouwer, the Netherlands, in bale form, are used in this study without further processing. Class F fly ash (FA) and ground granulated blast furnace slag (GGBFS) from the Netherlands are also employed. The average particle sizes (d_{50}) of FA and GGBFS are determined to be 13.9 µm and 19.3 µm, respectively, using a laser particle size analyzer (Mastersizer 2000). Chemical composition analysis of FA and GGBFS is performed via X-ray fluorescence spectrometry (XRF) (PANalytical Epsilon 3), with their loss on ignition (LOI) determined between 105 and 1000°C, as detailed in Table 1.

Table 1
Chemical composition of FA and GGBFS.

Oxides (wt%)	FA	GGBFS
SiO_2	54.57	29.41
Al_2O_3	21.60	13.21
Fe_2O_3	9.04	0.37
CaO	6.12	41.67
K_2O	2.85	0.42
MgO	1.17	8.57
SO_3	0.41	2.64
Other	2.13	1.07
LOI (1000°C)	2.11	1.15
Specific density (kg·m^{-3})	2225	2760

The stalk of the barley straw used in this study is, on average, wider and fuller than that of the wheat straw. The barley straw features a combination of macropores (~100–500 µm) and mesopores (10–50 µm), as well as a thicker stalk wall. This results in a less dense structure for barley straw, with a particle density of 872 kg·m^{-3} compared to 1013 kg·m^{-3} for wheat straw. Detail physical properties and chemical composition can be found in [30].

The alkali activator used in this study comprises sodium silicate solution (27.7 % SiO_2, 8.4 % Na_2O and 63.9 % H_2O) and sodium hydroxide (NaOH) pellets. Sodium hydroxide solutions of 0.5 M and 1.0 M are prepared for fibre treatment.

2.2. Design Parameters and Manufacturing Methods

This study refers to the optimized parameters from the study [4], which include a blend weight ratio of 95 % FA and 5 % GGBFS for the precursor, an alkali activator with a modulus of 1.8 and Na_2O concentration of 8 %, a water-to-dry components ratio of 0.4, and a weight percentage of fibres set at 30 % of the total dry weight (fibres and dry geopolymer).

The fibre treatment process involves a 24-hour immersion in a sodium hydroxide solution at room temperature, followed by a rinse with water to remove any residual alkali and impurities. The fibres are then dried under ambient conditions. Alkali activators are synthesized in advance by blending a sodium silicate solution, sodium hydroxide pellets, and additional water to achieve the desired composition.

During the main production process, the fibres are pre-wetted by spraying with water at a ratio of 0.4 water-to-fibre to achieve uniform binder distribution during mixing. The precursor materials and alkali activator solution are then mixed until a homogeneous paste is achieved. This geopolymer mixture is applied to the fibres and thoroughly mixed to ensure optimal binder coating on the surfaces. The resulting mixture is transferred into a mould and compressed overnight, with the coated straws being deagglomerated during the forming process to ensure a uniform mixture. After 24 hours, the compressed board is removed from the mould, wrapped in plastic foil, and cured overnight in an oven at 60°C for 24 hours. Following the curing process, the plastic is removed, and the board is further dried in an oven at 60°C for another 12 hours. The board is then removed from the oven, representing the final SGB, and trimmed to its final dimensions (300x200x15 mm^3).

This study includes two different Wood Wool Geopolymer Boards (WWGB), one with fibre treatment (0.25 M NaOH treatment) and one without. For the Straw Geopolymer Boards (SGB), six different samples are fabricated, involving two design parameters: straw types (barley and wheat straws) and NaOH concentration for fibre treatment (0 M, 0.5 M, and 1.0 M). Fig. 1 shows the SGB and WWGB samples manufactured for this study.

2.3. Environmental Assessment

In this study, the life cycle assessment (LCA) method conforms to EN 15804 +A2 [32], which provides standardized product category rules for construction products. Notable amendments compared to the

Fig. 1. SGB and WWGB samples (with their fibre components) manufactured for this study.

previous version, EN 15804 +A1 [33], include an expansion of core environmental impact indicators from 7 to 13, with further subdivisions such as global warming potential and eutrophication. Additionally, it is now obligatory to encompass life cycle stages beyond cradle to gate (modules A1-A3), extending to end of life (modules C1-C4) and benefits and loads beyond the system boundary (module D) for all construction products, with no exemption granted to products containing biogenic carbon. However, in this study, the focus is on comparative analysis, assuming similar life cycle profiles for modules C and D for WWCB, WWGB and SGB. This includes incineration of discarded boards at the

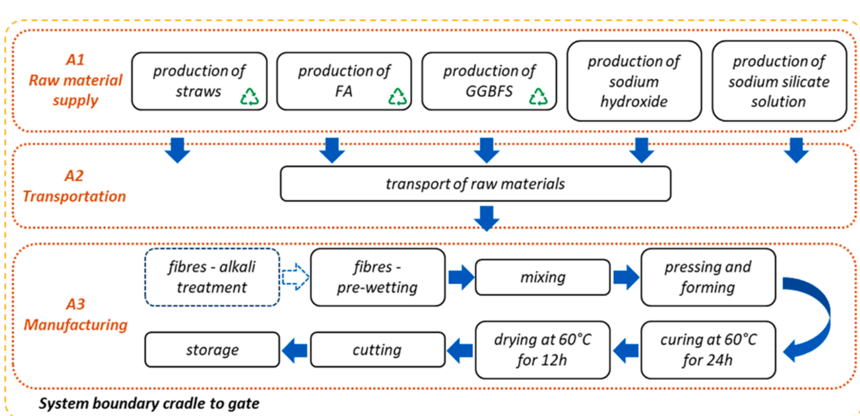

Fig. 2. LCA system boundary applied for the life cycle assessment for modules A1-A3.

end-of-life cycle and similar benefits from energy production through incineration for all. Alternatively, both geopolymer and OPC-based boards are assumed to be crushed and utilized for different applications at their end-of-life stages (C1–4) [34]. Therefore, modules C and D are excluded, with only modules A1-A3 considered. Fig. 2 illustrates the applied system boundary applied for the LCA, encompassing raw material supply (A1), transportation (A2), and manufacturing (A3).

Thirteen core environmental impact indicators and six additional indicators as per EN 15804 +A2 [32] are included in the analysis. Additionally, a single weighted scope (SWS) on these characterized indicators is incorporated, calculated following guidelines from [35]

$$SWS = \sum_{i=1}^{n} \frac{characterized\ indicators_i}{NF_i} x \quad WF_i \tag{1}$$

where the normalized factors (NF) are based on Environmental Footprint (EF) 3.1 [36], and weighting factors (WF) are based on [37].

Two life cycle inventory databases are utilized: Ecoinvent 3.8 (Nov 2021) and Agri-footprint version 6 (June 2022). Additionally, environmental product declaration (EPD) for FA and GGBFS are referenced. Table 2 details the inputs and their corresponding data sources, with LCA software SimaPro 9.4 employed for the calculation.

To investigate the impact of the allocation method on life cycle analysis, three allocation scenarios are included in the study. Scenario 1 aligns with the European Waste Framework Directive [13], considering FA and GGBFS as by-products while treating straws as waste. Scenario 2 considers all FA, GGBFS and straws as by-products, taking part of the environmental burden from their main productions, i.e. coal power production to FA, pig iron production to GGBFS, and crops harvesting to straws. Scenario 3 considers FA, GGBFS and straws as waste rather than by-products, taking no burden from their main productions.

2.4. Module A1 – raw material supply

The FA utilized in this study was originally supplied by Vliegasunie B.V., Culemborg, now handled by BauMineral GmbH. The EPD for FA from BauMineral GmbH is referenced [38,40], where the system boundary commences after the electrostatic precipitator in the coal power plant, without allocation from the main coal power generation. GGBFS is originally sourced from ENCI, IJmuiden. In the absence of an EPD from ENCI, the EPD from a similar local supplier, Ecocem,

Table 2
Input to life cycle assessment for modules A1-A3.

Input	Data sources	Data unit and descriptions
Barley straw	*Agri-footprint 6*	*1 kg Barley straw at farm {NL} Economic.*
Wheat straw	*Agri-footprint 6*	*1 kg Wheat straw at farm {NL} Economic.*
Straw handling	*Ecoinvent 3.8*	*1 p Baling {RoW}| processing*
Straw handling	*Ecoinvent 3.8*	*1 p Bale loading {RoW}| processing*
Wood wool	*Ecoinvent 3.8*	*1 kg Wood wool {RER}*
Sodium hydroxide	*Ecoinvent 3.8*	*1 kg Sodium hydroxide, without water, in 50 % solution state {RER}*
Sodium silicate	*Ecoinvent 3.8*	*1 kg Sodium silicate, without water, in 37 % solution state {RER}*
FA	*EPD*	*1 ton fly ash [38]*
(allocation)	*Ecoinvent 3.8*	*1 kWh Electricity high voltage {NL}| electricity production. hard coal*
GGBFS	*EPD*	*1 ton ground granulated blast furnace slag [39]*
(allocation)	*Ecoinvent 3.8*	*1 kg Pig iron {RER}| pig iron production*
OPC	*Ecoinvent 3.8*	*1 kg Cement Portland {Europe without Switzerland}*
Water	*Ecoinvent 3.8*	*1 kg Tap water {RER}*
Transport	*Ecoinvent 3.8*	*1 tkm Transport freight lorry 16–32 metric ton euro6 {RER}*
Energy	*Ecoinvent 3.8*	*1 kWh Electricity low voltage {NL}*

[Geographies classification in databases: NL-Netherlands; RER-Europe; RoW-World;]

Moerdijk, is referenced [39]. The EPD's system boundary starts from the quenching process and the subsequent drying and milling processes, without taking allocation from the blast furnace operation for steel production. Assumptions are made to establish the economic allocation scenarios for FA and GGBFS. Based on [23], 1 kg of pig iron production is associated with 0.24 kg of slag as a by-product and 1 kWh of electricity power generation is associated with 0.367 kg of coal as a fuel source and 0.052 kg of FA as a by-product. Economic allocation of FA and GGBFS is based on [12], with 2.59 % from pig iron production and 1 % from coal power production allocated to slags and FA production.

Economic allocation for barley and wheat straws is available in the Agri-footprint database, with no allocation scenario estimated by calculating the straw handling process. Notably, the Agri-footprint database does not consider biogenic carbon storage; therefore, the uptake of biogenic carbon is approximated using standard EN 16449 [41].

2.5. Module A2 – transportation

Wheat and barley are cultivated extensively in regions including North Brabant, with 7 % and 11 % of land use per region per crop type [42] respectively. Tree farming and sawmills are also present in North Brabant [42,43]. All fibres (wheat straw, barley straw, and wood wool) are assumed to be locally sourced within this region, with an estimated distance of 50 km from the source to the production site (Eindhoven). Two coal power plants are operational in the Netherlands, namely Maasvlakte and Eemshaven power stations [44]. The FA used is obtained from Vliegasunie, Culemborg and processed at their Maasvlakte plant, with minimal additional processing [45]. There is only one active blast furnace steel plant in the Netherlands [46], where the raw material blast furnace slag (BFS) is obtained. The GGBFS is supplied by HeidelbergCement ENCI, Ijmuiden, and the BFS is further processed (dying and milling) into GGBFS. Both materials are transported approximately 150 km from their sources. Freight transport category Euro 6 is applied [47] in this study.

2.6. Module A3 – manufacturing

Energy consumption (E) required for curing and drying processes is approximated using [11]

$$E = \quad P_{oven} \bullet t + m \bullet C_p \bullet (T - T_{amb}) \tag{2}$$

where P_{oven} is the power of the oven, t is the curing or drying time, m is the mass of specimens, C_p is the specific heat capacity of specimens, T is the curing or drying temperature, and T_{amb} is the ambient temperature. The first term describes energy used to maintain temperature, and the second term describes energy used to heat materials. The first term can be further generalized by assuming a steady rate of heat transfer between the oven and the ambient environment:

$$P_{oven} = \quad S_{oven} \bullet \lambda_{oven} \bullet (T - T_{amb}) \tag{3}$$

where S_{oven} is the conduction shape factor of the oven, and λ_{oven} is the effective thermal conductivity of the oven wall [48]. The estimation of energy consumption is based on the lab equipment utilized in this study.

2.7. Physical characteristics

To ascertain the viability of substituting raw materials in WWCB, specifically with SGB, an investigation into the physical characteristics of SGB is conducted and subsequently compared with those of WWGB.

The mechanical properties, including compressive and bending strengths, are evaluated using a mechanical testing system (Instron 5967) equipped with a 5 kN load cell. Compressive strength at 10 % deformation (σ_{10}) is determined following the procedure outlined in EN 826 [49]. Test specimens measuring 50x50x15 mm^3 are prepared from the samples. The compression stress at a strain of 10 % (σ_{10}) is recorded, with the minimum required σ_{10} at 20 kPa [50] serving as the reference for compressive strength evaluation. For the measurement of bending strength, the testing method specified in EN 12089 [51] is applied. Samples are cut into dimensions of 150x125x15 mm^3. The maximum force exerted during the bending test is recorded to calculate the bending strength (σ_b), with the minimum required σ_b value of 1700 kPa [50] considered as the reference for bending strength assessment.

Thermal conductivity (λ) is determined using the transient line source method with a thermal needle probe (AP Isomet model 2104). The probe, known for its accuracy of 5 % of the reading plus 0.001 $W\cdot m^{-1}\cdot K^{-1}$, is employed under standardized conditions, with all samples conditioned at a relative humidity of 50 $\pm$ 5 %. Measurements are conducted at room temperature (20 $\pm$ 2°C), with three readings taken at different locations on each board to account for potential variation within the sample.

The hygroscopic sorption properties of the samples are determined following standard ISO 12571 [52]. Sorption isotherms are measured by the saturated salt solutions method, covering specific relative humidity levels ranging from 0 % to 85 %. Moisture uptake is monitored by weighing the samples at 24-hour intervals using a digital balance until a constant mass is reached, defined as three successive weighings showing a mass loss change of less than 0.1 %.

Microstructure analysis is conducted through an optical microscope (ZEISS Axio Imager 2).

Particle density is determined using a helium pycnometer (Micromeritics AccuPyc II 1340) with a 10 cm^3 cup is used. The pycnometer has a reading accuracy of 0.03 % and an additional 0.03 % uncertainty related to the sample capacity.

Chemical composition analysis is performed using Fourier transform-infrared (FT-IR) spectroscopy in conjunction with an attenuated total reflection (ATR) attachment (PerkinElmer Frontier FT-IR). This technique facilitates the identification and characterization of functional groups present in the samples, with spectra collected over a wavenumber range of 4000–400 cm^{-1} at a resolution of 1 cm^{-1}.

Thermogravimetric analysis (TGA) is employed to assess mass loss or decomposition events to temperature, utilizing a thermogravimetric analyser (TA Instruments TGA Q500). The heating process, starting from room temperature and continuing up to 1000°C at a rate of 10°$C\cdot min^{-1}$, is conducted under a controlled nitrogen atmosphere with a constant flow rate of 60 $ml\cdot min^{-1}$.

3. Results and discussions

3.1. Physical characteristics

The primary interconnecting structures within the composites are formed by the aluminosilicate hydration products of the geopolymer. The activator creates an alkaline environment in the mixture, facilitating the dissolution of silicate and aluminate from FA and the release of calcium from GGBFS. C-N-A-S-H type gel is assumed to be predominantly formed as the primary aluminosilicate gel [4]. Compared to WWGB samples, the geopolymer gels do not adhere as effectively to the surface of the straws in SGB samples. SGB samples made with untreated straws, both Sw0 and Sb0, display the weakest binder-to-straw adhesion, with partially coated straws detaching from the board during handling. For treated straws, the geopolymer binder exhibits improved coverage, but small areas of exposed straws can still be observed on all SGB samples, as depicted in Fig. 3 for Sw1 and Sb1.

Fig. 4a illustrates the bending strength of the samples. It is evident that all SGB samples, irrespective of fibre treatment, exhibit lower strength than WWGB and do not meet the minimum bending strength requirement specified in EN 13168 for a 15 mm thick board (1.7 MPa) [50]. Overall, wheat-based SGB demonstrates better bending strength compared to barley-based SGB. SGB samples incorporating treated straws demonstrate higher bending strengths due to the removal of non-cellulose components and the presence of mercerised cellulose structures, which enhance adhesion with the geopolymer gels [6,31]. However, the bending strength for Sw2 is lower than Sw1, indicating the dissolution of core cellulose structure within wheat straws under higher NaOH concentrations. Additionally, the structural cellulose of treated straws may undergo further alkaline hydrolysis during the geopolymerisation process, further weakening the cellulose structure. Conversely, the bending strength for Sb2 is slightly higher than Sb1, suggesting that barley straws remain more intact. This observation aligns with the higher lignin and wax-to-cellulose ratio for barley straws [30]. Higher alkali concentration is therefore necessary to significantly affect the structural cellulose.

The compressive strength is mainly derived from the formation of aluminosilicate hydration products providing interconnecting strength within the composites [4]. SGB exhibits lower compressive stresses at 10 % strain (σ_{10}) than WWGB, as shown in Fig. 4b. However, all samples meet the minimum requirement specified in EN 13168 (0.02 MPa) [50] for handling purposes. Sb2 exhibits better compressive strength compared to Sw2, indicating a higher degree of fibrillation on treated barley straw compared to wheat straw, providing additional interfacial bonding between the fibres and geopolymer gels. However, this high

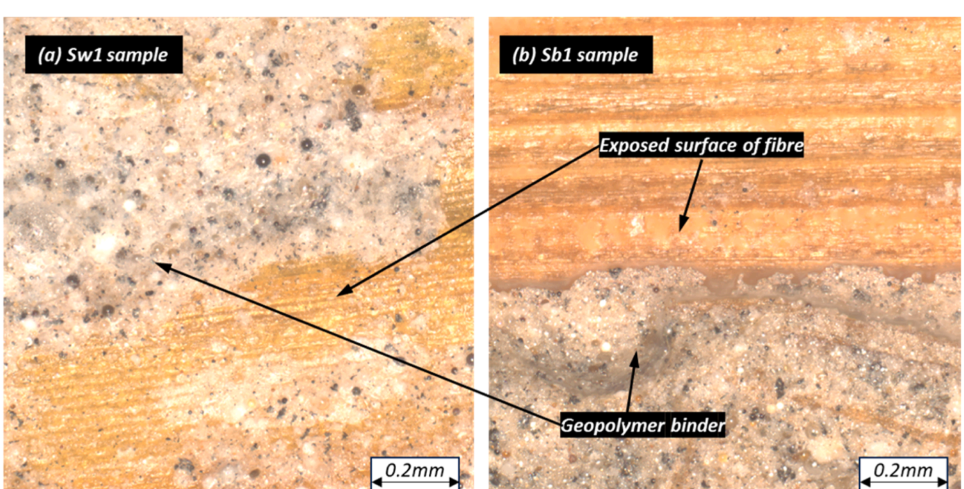

Fig. 3. Geopolymer binder and exposed surface of straw fibres for sample Sw1 and Sb1.

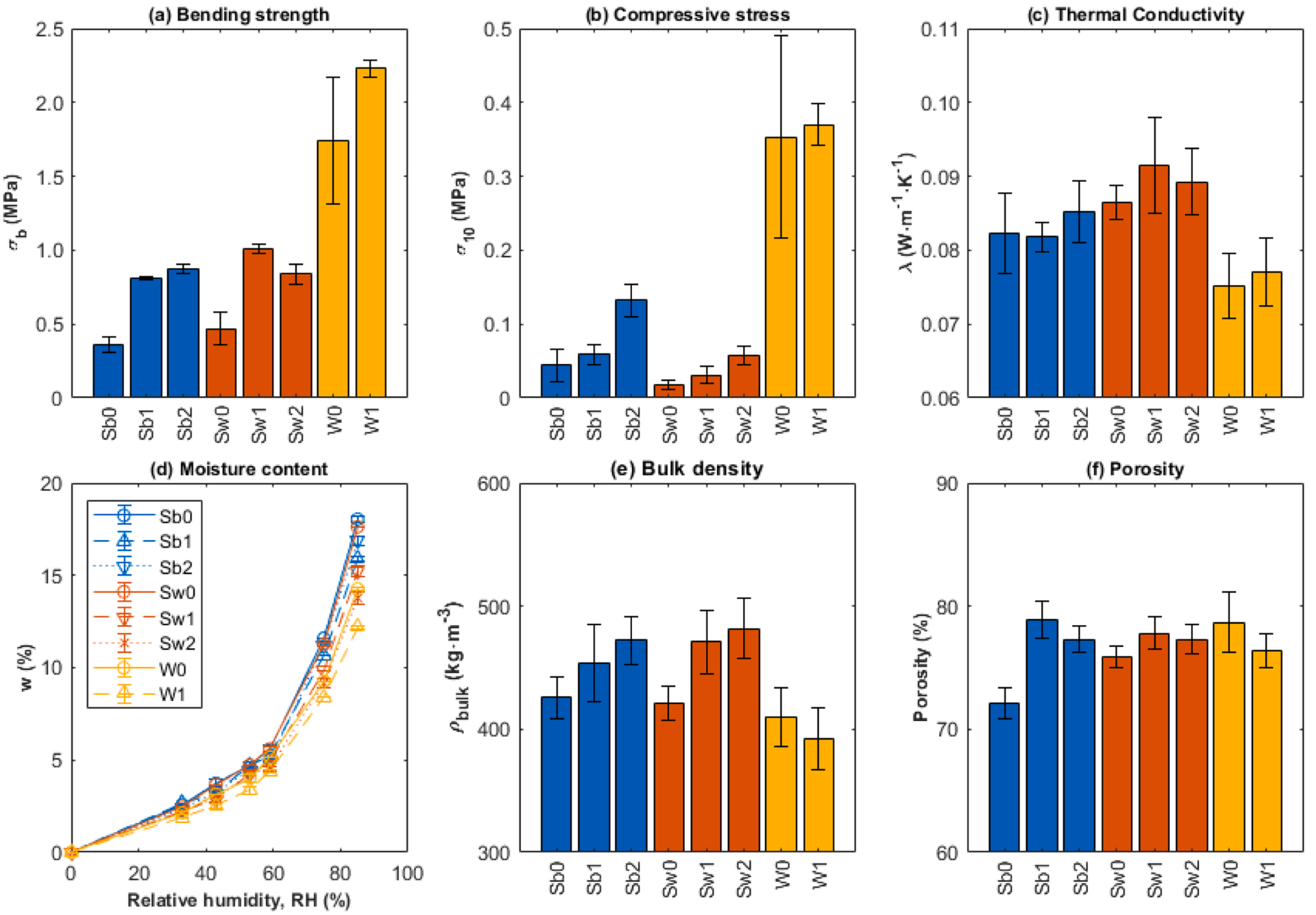

Fig. 4. (a) bending strength, (b) compressive strength, (c) thermal conductivity, (d) sorption isotherms, (e) bulk density, and (f) porosity of SGB and WWGB samples.

degree of fibrillation compromises bending strength.

Fig. 4c shows the thermal conductivity of the samples. Overall, barley-based SGB has slightly lower thermal conductivities than wheat-based SGB, attributed to the different microstructures of their fibres. Barley straw has larger pores and thicker wall structures [30], which could lower the overall thermal conductivity of their composite. An increasing trend is observed when treated fibres are utilized, indicating a denser structure encouraging heat transfer. SGB has slightly higher thermal conductivity than WWGB, possibly due to thicker geopolymer binder forming in cluster areas on straws compared to a more homogeneous layer on wood wool. The specific heat capacity of the SGB samples ranges from 600 to 800 $J{\cdot}kg^{-1}{\cdot}K^{-1}$, indicating low thermal storage capacity. This suggests that heat is more likely to diffuse through the boards rather than being retained.

Fig. 4d shows the sorption isotherms of SGB and WWGB samples. Overall, sorption for both SGB and WWGB decreases when treated fibres are utilized, attributed to the alkali treatment degrading the cell wall material and reducing the number of hydroxyl groups accessible to water, resulting in increased hydrophobicity [31,53]. Barley-based SGB exhibits a higher sorption capacity, followed by wheat-based SGB and then WWGB, correlated with the existence of macropores in barley straw [30] compared to wheat straws and wood wool.

The bulk density and porosity of SGB and WWGB are shown in Figs. 4e and 4 f. Generally, SGB made with treated straws have higher bulk densities than those made of untreated straws, confirming a higher amount of geopolymer binder bonded to the treated fibres. Wheat-based SGB has slightly higher densities than barley-based SGB but lower compressive strength, indicating uneven distribution and adherence of aluminosilicate products to wheat-based SGB, agglomerating in the composite. It can be seen that Sb2 has a higher bulk density but lower porosity than Sb1, similarly between Sw2 and Sw1, indicating that at a more widely distributed gel formation on the straws treated with 1.0 M NaOH compared to 0.5 M NaOH. Conversely, WWGB has lower bulk densities than SGB but significantly higher compressive strength, indicating a lower gel-to-fibre ratio, with a thin layer but interconnected gel network formed in the composite, providing necessary strength at lower bulk density.

The effect of alkali treatment on straws is further verified using FTIR and TGA and presented in Appendix A. While leaching tests on the SGB samples were not conducted in this study, previous research [54] has shown that FA-based geopolymers are effective in immobilizing several heavy metals.

Overall, SGB performs poorly compared to WWGB, even when alkali-treated straws are utilized to improve adhesion with the geopolymer gels. Therefore, utilizing alternative non-wood fibres such as straws, as a substitute for wood wool, reveals disadvantages in overall performance, making it a less attractive solution.

3.2. Environmental assessment

Fig. 5 presents the cradle-to-gate environmental impact indicators, as per EN 15804 +A2, for straw geopolymer board (SGB) and wood wool geopolymer board (WWGB), in comparison to wood wool cement board (WWCB). Both wheat-based SGB and barley-based SGB exhibit similar impact profiles, with only wheat-based SGB (Sw0, Sw1, and Sw2) shown for clarity. Under allocation scenario 3, which considers straws, FA, and GGBFS as waste rather than by-products, the lowest impacts are generally observed. Conversely, allocation scenario 2, where FA, GGBFS

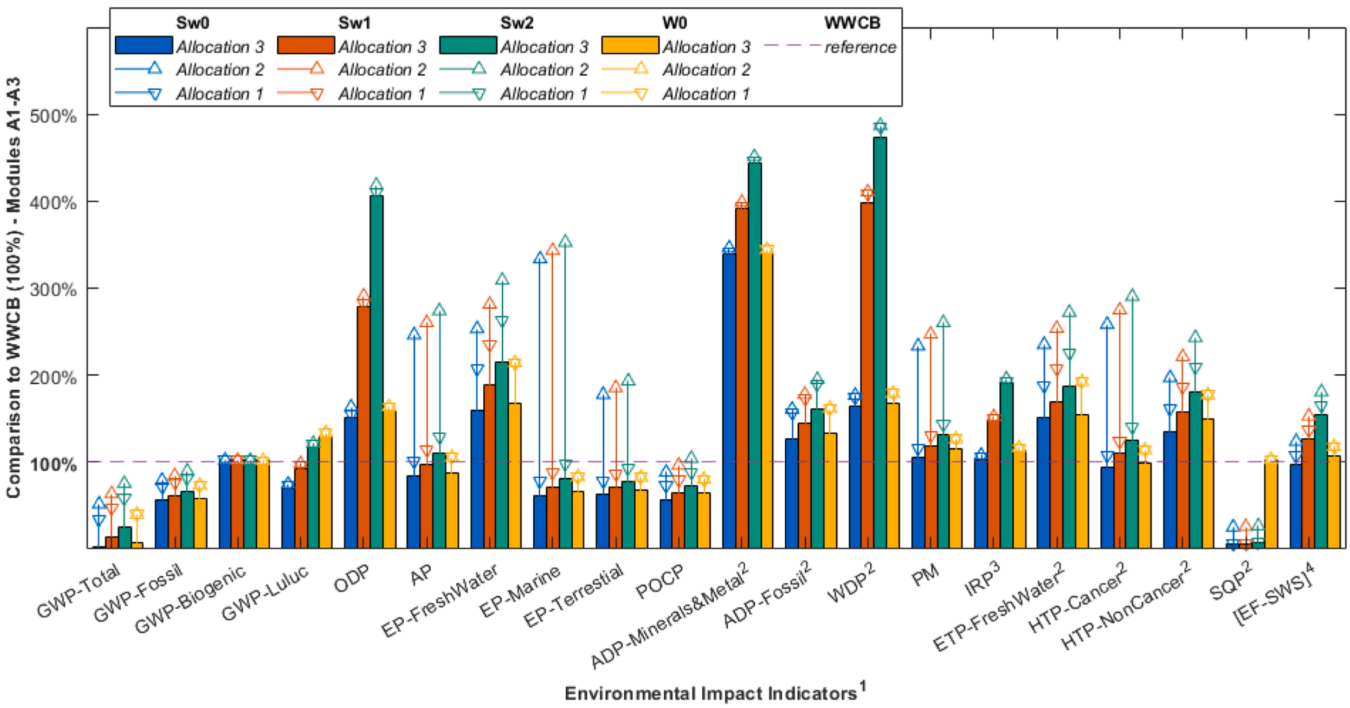

Fig. 5. Core and optional environmental impact indicators of SGB and WWGB relative to WWCB, modules A1-A3, under different allocation scenarios (1-marker-∇, 2-marker-Δ, 3-bar). [1. global warming potential (GWP); land use and land use change (luluc); depletion potential of the stratospheric ozone layer (ODP); Acidification potential (AP); eutrophication potential (EP); formation potential of tropospheric ozone (POCP); abiotic depletion potential (ADP); water deprivation potential (WDP); particulate matter emissions (PM); ionizing radiation potential (IRP); eco-toxicity (ETP); human toxicity potential (HTP); soil quality potential (SQP) 2. The results of these environmental impact indicators should be used with care as there is limited experience with the indicators and the uncertainty is high. 3. This impact category deals mainly with the eventual impact of low-dose ionizing radiation on the human health of the nuclear fuel cycle. It does not consider effects due to possible nuclear accidents, occupational exposure or radioactive waste disposal in underground facilities. Potential ionizing radiation from the soil, radon and some construction materials is also not measured by this indicator. 4. Additional single weighted score (SWS) based on the Environmental footprint (EF) method. GWP-biogenic is excluded from the calculation.].

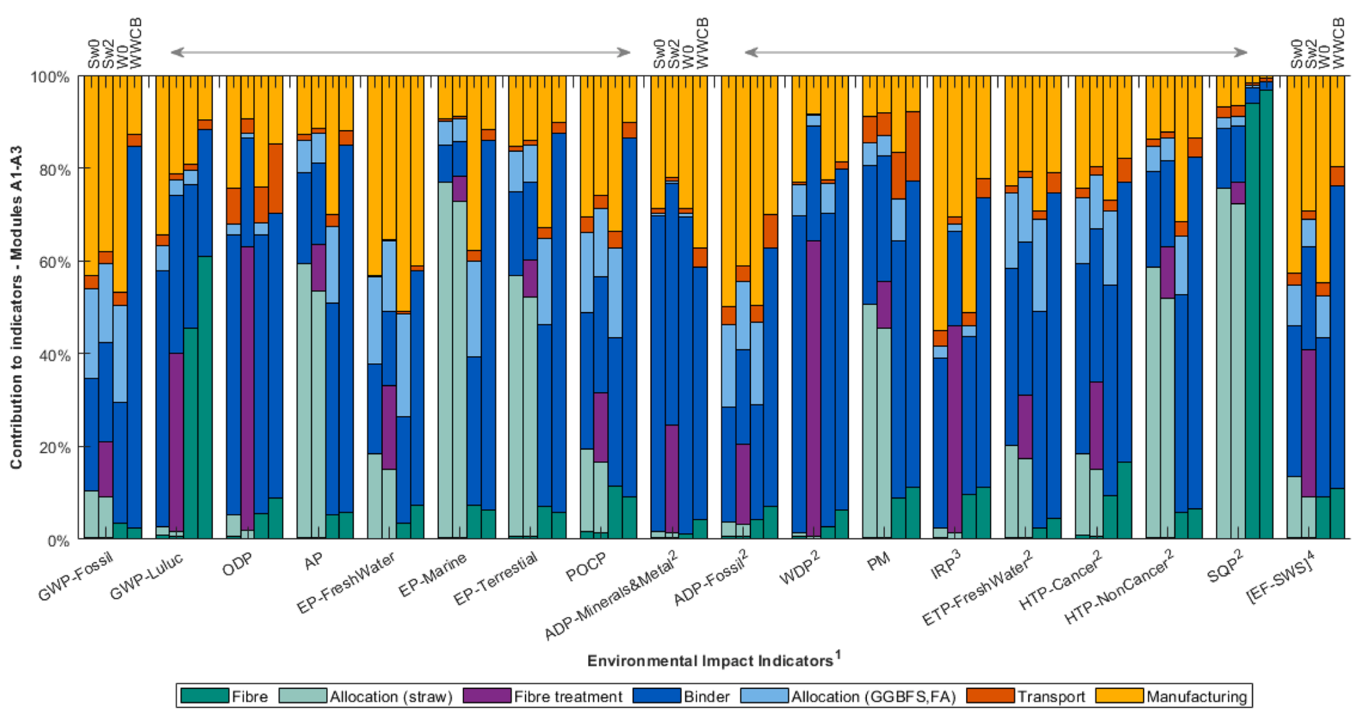

Fig. 6. Percentage contribution to different environmental impact indicators for SGB, WWGB and WWCB, based on component groupings under the Allocation 2 scenario. Global warming potential total (GWP-total) and biogenic (GWP-biogenic) are excluded from the chart for clarity. [1, 2, 3, 4. Similar notes as per Fig. 5].

and straws are treated as by-products, has the highest impact due to taking on part of the environmental burden from their main productions. Surprisingly, under all allocation scenarios, both SGB and WWGB demonstrate higher environmental impacts across more than half of the 19 impact categories compared to WWCB. Under a no-allocation scenario, 10 and 12 impact indicators are higher for Sw0 and W0, respectively, increasing to 14 under a full-allocation scenario. Using the single weighted score based on the Environmental Footprint (EF-SWS) method, only Sw0 under a no-allocation scenario demonstrates a lower score than WWCB. Sw2 under a full-allocation scenario emerges as the worst case, with 16 out of 19 indicators showing higher impacts than WWCB, with EF-SWS as high as 181 % compared to WWCB under a full-allocation scenario, strongly suggesting overall adverse environmental impacts from fibre alkali treatment.

Fig. 6 details the percentage contribution from different components (fibres, binders, treatment, transport, manufacturing, allocation). Generally, binders, both OPC and geopolymer, dominate most indicators, followed by the manufacturing process, primarily heat curing and drying in the oven. This emphasizes that while substituting OPC with geopolymer can reduce embodied carbon in module A1 (raw material), the need for heat curing in FA-based geopolymer increases impacts in module A3 (manufacturing). Alkali treatment on fibre is another major contributor, commonly used to modify fibre properties, especially when employing agricultural waste or by-products as alternative raw materials for building materials. Transportation is minimal in general as all materials are assumed to be locally sourced in the Netherlands, but it could become a dominant factor if raw materials are not locally produced.

Specifically, substituting OPC with geopolymer as a binder significantly reduces GWP from fossil fuel (GWP-fossil) by avoiding the energy-intensive production of OPC. Replacing wood wool with straws reduces GWP from land use (GWP-luluc) and water use (SQP) by avoiding timber harvesting for wood wool production.

Treating FA and GGBFS as by-products leads to significantly increased impact categories such as climate change, eutrophication, and human toxicity. Similarly, higher impact indicators can also be seen when straws are treated as by-products. The influence of treating these materials as waste or by-products is summarized in Table 3, aligning with calculations from [12]. Based on EF-SWS, there is a 6-fold increase in FA, and an 8-fold increase in GGBFS for the weighted average of all impact categories, when environmental burdens from coal power and pig iron productions are allocated. Similarly, a substantial 30-fold and 35-fold increase in wheat and barley straws occurs respectively when the burden from crop production is allocated to them.

Fig. 7 further details the contribution of different components to indicator GWP-fossil. Geopolymer binder reduces overall emissions under all allocation scenarios, but the need for heat curing on FA-based geopolymer diminishes this reduction. Under allocation scenario 2 (all economic allocation), there is a total reduction of 27 % in GWP-fossil from WWCB to W0 and a reduction of 21 % from WWCB to Sw0. If following the current practice where FA and GGBFS are considered as by-products but straws as waste (allocation scenario 1), a total reduction of 29 % in GWP-fossil for Sw0 is accounted for. Allocation scenario 3, considering FA, GGBFS, and straws as waste, results in a total reduction of 42 % for W0 and 44 % for Sw0 from WWCB. However, in the context of the Netherlands, where FA and GGBFS are treated as by-products, allocation scenario 3 may under-account. Notably, GGBFS allocation based on physical and chemical partitioning by the steel industry is higher than the allocation by economic value applied in this study [22]. Since the same fibre mass is used in the design of SGB and WWGB, no significant difference is expected in the biogenic carbon stored in these boards, which will be released into the atmosphere at the end of their life cycle, accounting for module C1-C4 which are not included in this study.

Fig. 8 shows the percentage change in GWP-fossil under different parameters, using sample Sw2 under allocation scenario 1 as the benchmark. Overall, for every 1 % increase in Na_2O concentration and 0.1 increase in SiO_2-to-Na_2O modulus of the alkali activator, an increase of 2.5 % and 0.7 % occurs respectively. Conversely, increasing the percentage of GGBFS in FA-based geopolymer precursor does not significantly affect GWP. However, the local availability of FA and GGBFS plays a significant role in transportation emissions. An increase of 1 tkm between the raw material supplier and end production facility leads to a 0.5 % increase in GWP. With the phasing out of blast furnace facilities and coal power plants, the local availability of FA and GGBFS

Table 3
Environmental impact of wheat straw, barley straw, FA and GGBFS for different impact indicators, per kg of raw material, based on no allocation and economic allocation.

Impact Indicator[1]	Unit	Wheat straw		Barley straw		FA		GGBFS	
		No allocation	*Economic allocation*	*No allocation*	*Economic allocation*	*No allocation*	*Economic allocation*	*No allocation*	*Economic allocation*
GWP-Total	*kg CO_2 eq.*	*−1.7E+ 00*	*−1.4E+ 00*	*−1.7E+ 00*	*−1.4E+ 00*	*3.5E−02*	*2.3E−01*	*3.2E−02*	*2.1E−01*
GWP-Fossil	*kg CO_2 eq.*	*1.1E−02*	*2.5E−01*	*1.1E−02*	*2.8E−01*	*3.5E−02*	*2.3E−01*	*3.2E−02*	*2.1E−01*
GWP-Biogenic	*kg CO_2 eq.*	*−1.7E+ 00*	*−1.7E+ 00*	*−1.7E+ 00*	*−1.7E+ 00*	*−1.3E−04*	*−6.1E−04*	*2.9E−05*	*−5.4E−04*
GWP-luluc	*kg CO_2 eq.*	*9.4E−06*	*2.8E−05*	*9.4E−06*	*3.2E−05*	*4.2E−06*	*2.8E−05*	*9.8E−06*	*6.1E−05*
ODP	*kg CFC11 eq.*	*1.1E−09*	*1.0E−08*	*1.1E−09*	*1.1E−08*	*8.5E−10*	*2.6E−09*	*4.7E−09*	*1.2E−08*
AP	*mol H+ eq.*	*7.4E−05*	*1.0E−02*	*7.4E−05*	*1.2E−02*	*1.0E−04*	*6.3E−04*	*1.3E−04*	*8.0E−04*
EP-FreshWater	*kg P eq.*	*2.0E−06*	*2.2E−04*	*2.0E−06*	*2.9E−04*	*1.6E−05*	*1.2E−04*	*9.6E−07*	*7.3E−05*
EP-Marine	*kg N eq.*	*2.5E−05*	*4.9E−03*	*2.5E−05*	*4.8E−03*	*2.6E−05*	*1.6E−04*	*3.6E−05*	*1.9E−04*
EP-Terrestial	*mol N eq.*	*2.7E−04*	*2.1E−02*	*2.7E−04*	*2.4E−02*	*2.6E−04*	*1.6E−03*	*4.1E−04*	*2.1E−03*
POCP	*kg NMVOC eq.*	*8.2E−05*	*9.7E−04*	*8.2E−05*	*9.9E−04*	*6.7E−05*	*4.1E−04*	*1.1E−04*	*1.0E−03*
ADP-Mineral&Metal[2]	*kg Sb eq.*	*9.5E−08*	*4.1E−07*	*9.5E−08*	*4.6E−07*	*7.8E−08*	*1.4E−07*	*6.7E−08*	*2.0E−07*
ADP-Fossil[2]	*MJ*	*2.0E−01*	*1.0E+ 00*	*2.0E−01*	*1.0E+ 00*	*3.8E−01*	*2.5E+ 00*	*4.8E−01*	*2.3E+ 00*
WDP[2]	*m^3 depriv.*	*3.3E−03*	*7.0E−03*	*3.3E−03*	*7.7E−03*	*5.3E−04*	*1.4E−02*	*1.7E−03*	*1.1E−02*
PM	*disease inc.*	*4.0E−10*	*5.0E−08*	*4.0E−10*	*5.8E−08*	*4.4E−10*	*2.0E−09*	*7.9E−10*	*1.3E−08*
IRP[3]	*kBq U−235 eq.*	*6.4E−04*	*4.0E−03*	*6.4E−04*	*4.7E−03*	*4.4E−04*	*2.2E−03*	*6.2E−04*	*3.9E−03*
ETP-FreshWater[2]	*CTUe*	*1.6E−01*	*1.0E+ 01*	*1.6E−01*	*1.3E+ 01*	*6.0E−01*	*4.1E+ 00*	*1.8E−01*	*5.6E+ 00*
HTP-Cancer[2]	*CTUh*	*9.6E−12*	*2.2E−10*	*9.6E−12*	*2.6E−10*	*5.8E−12*	*3.1E−11*	*1.4E−11*	*9.9E−10*
HTP-NonCancer[2]	*CTUh*	*1.8E−10*	*3.5E−08*	*1.8E−10*	*4.1E−08*	*3.4E−10*	*1.6E−09*	*2.1E−10*	*4.0E−09*
SQP[2]	*Pt*	*5.3E−02*	*2.3E+ 01*	*5.3E−02*	*2.9E+ 01*	*7.7E−02*	*3.6E−01*	*6.9E−02*	*4.3E−01*
EF-SWS[4]	*Pt*	*2.0E−04*	*6.1E−03 (Δ 30-fold)*	*2.0E−04*	*7.0E−03 (Δ 35-fold)*	*3.2E−04*	*2.0E−03 (Δ 6-fold)*	*3.2E−04*	*2.5E−03 (Δ 8-fold)*

[1, 2, 3, 4. Similar notes as per Fig. 5]

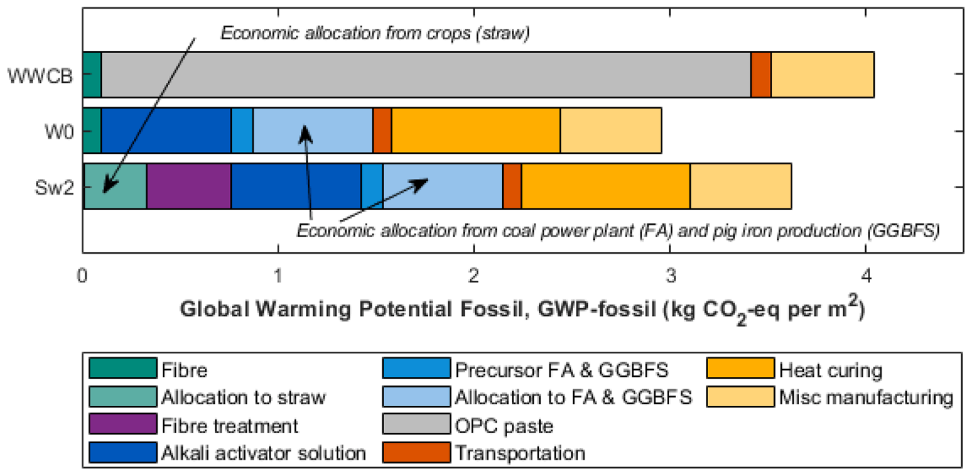

Fig. 7. Global warming potential fossil fuel (GWP-fossil) and global warming potential total (GWP-total) for Sw2, W0 and WWCB under allocation 2 scenario, showing contributions from different materials and processes.

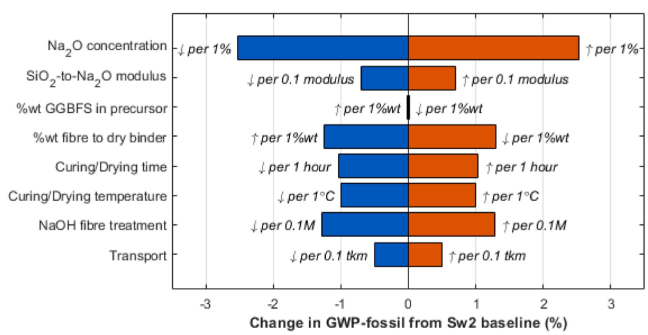

Fig. 8. Change in GWP-fossil against change in design parameters used in this study, based on sample Sw2 under allocation scenario 1.

may diminish, rendering their use as precursors impractical and resulting in higher GWP. Alternative precursors from other waste sources, for example, wastepaper sludge ash [55], need to be explored. Similarly, the local availability of fibre sources is crucial. While both straws and wood wool are assumed to be equidistant in this study, local availability should be a primary consideration when seeking substitutions. Additionally, treatments such as alkali treatment applied to straws in this study significantly reduce the environmental benefits of using agricultural waste as alternative fibres. An increase of up to 1.3 % is expected for every additional 0.1 M NaOH concentration. However, the recovery and recycling of waste alkali solutions after fibre treatment, which may reduce their environmental impacts, are not considered in this study. Curing temperature and duration significantly influence GWP, with each increment of 1°C and 1 hour resulting in a 1.0 % and 1.3 % increment in GWP, respectively. Therefore, optimal curing temperature and time, including drying requirements, should be carefully considered with both technical and environmental factors in mind.

3.3. Recommendation for optimization and sustainability

Several improvements can be proposed to enhance the performance and sustainability of SGB, drawing on the findings from the physical characteristics and environmental assessments.

Alkali treatment of straw fibres was selected due to its established commercial application and its feasibility for direct implementation in straw geopolymer board (SGB) fabrication. However, the treatment proved less effective for wheat and barley straws, while also contributing significantly to the environmental footprint. This highlights the need to explore alternative treatment methods, such as mechanical treatments, coating, other eco-friendly chemical treatment, or a combination of multiple treatments.

As discussed in Section 3.2, heat curing is another significant contributor to the environmental impact of SGB production, primarily due to the energy-intensive nature of the process. The energy consumption in this study reflects the limitations of lab-scale equipment and the standard power grid in the Netherlands. At an industrial scale, energy usage per unit volume is expected to decrease considerably due to process efficiencies. Nevertheless, exploring low-energy curing methods, such as ambient curing or the use of accelerated curing agents, could further mitigate this issue. Incorporating renewable energy sources for power supply during the curing process represents an additional strategy for reducing the carbon footprint associated with SGB production.

The diminished performance of SGB compared to WWGB stems in part from differences in fibre structure. Commercially produced wood wool is optimized for board fabrication, featuring flat, thin strands that bond effectively with the binder. In contrast, the natural stalk form of the straws used in this study lacked these structural advantages. Addressing this limitation requires investigating alternative non-wood fibres, such as hemp, flax, grass, kenaf, bagasse, jute, coir, or bamboo. These materials should be evaluated for key characteristics, including flat surface area and moderate hydrophilicity, which could enhance compatibility with the geopolymer matrix. Furthermore, waste materials like recycled tire textile fibres [56,57] could serve as innovative substitutes for wood wool, offering potential performance and environmental advantages.

The geopolymer formulation and mixing techniques employed in this study were derived from previously optimized parameters [4] However, further refinement could significantly improve fibre adhesion and overall board performance. For instance, exploring GGBFS-based geopolymer [58] or other eco-friendly mixture [59] could enhance the binding properties of the geopolymer matrix. Additionally, the use of advanced mixing techniques, such as high-shear mixers or industrial-scale equipment, would likely result in more uniform fibre distribution and stronger matrix bonding compared to the manual fabrication methods used in this research.

Finally, the low mechanical strength of SGB could be addressed by adopting innovative board designs. A layered composite approach, with SGB as the core material and reinforced with stronger outer layers such as fiberglass or durable laminates, could substantially enhance bending strength while retaining the board's thermal insulation properties. Similarly, hybrid designs incorporating SGB into sandwich panels with complementary materials could enable broader applications in scenarios where strength and insulation are both critical.

4. Conclusion

This study explores the use of industrial and agricultural by-products as alternative raw materials in the production of insulation boards, specifically straw geopolymer boards (SGB). Here, straws serve as alternative fibres for wood wool, and geopolymer functions as a substitute for OPC.

The environmental impact indicators, as per EN 15804 +A2, are assessed for SGB and compared to wood wool geopolymer board (WWGB) and wood wool cement board (WWCB). The focus of the investigation is on the implications of allocation methods for the raw materials, namely FA, GGBFS, and straws. These materials are either treated as by-products, sharing part of the environmental burden from their main productions, or as waste, thus not accounting for any burden from their main productions. Treating FA and GGBFS as by-products results in significantly increased impact categories such as climate change, eutrophication, and human toxicity. A similar increase in impact indicators is observed when straws are treated as by-products.

Both SGB and WWGB exhibit higher environmental impacts across more than half of the 19 impact categories compared to WWCB. Binders (precursor and alkali activator) dominate most indicators, followed by heat curing and drying in the oven. This highlights the trade-off between embodied carbon reduction in module A1 (raw material) and heat curing in FA-based geopolymer in module A3 (manufacturing). Alkali treatment on fibre is another major contributor, especially when characteristic improvement is required for fibre substitution. Transportation plays a minimal role; however, it could become a dominant factor if raw materials are not locally produced.

When considering only global warming potential (GWP), substituting OPC with geopolymer binder reduces overall emissions under all allocation scenarios. However, substituting wood wool with straws does not provide additional environmental benefits, especially when fibre treatment and economic allocation scenarios are applied.

In terms of physical performance, SGB performs poorly overall compared to WWGB. Lower mechanical strengths are observed even when alkali-treated straws are utilized. Exposed straws are visible on SGB samples, indicating uneven distribution and adherence of aluminosilicate products to the straws. While alkali treatment of straws leads to delignification and improved adhesion with the geopolymer gels, the strength improvement is not sufficient before high NaOH concentration destroys the core cellulose structure of the straws, subsequently impacting its bending strength.

This study indicates the environmental benefits of substituting OPC with geopolymer in terms of global warming potential. However, it is less obvious when considering other impact indicators. Utilizing straws as a substitute for wood wool reveals disadvantages in overall performance, making it less attractive as a solution. The substitution of wood with other alternative non-wood fibres is challenging and does not guarantee better sustainability. For life cycle assessment, a consistent allocation method for by-products such as the economic allocation method is strongly recommended to avoid over or under-reporting environmental impacts across different industries.

CRediT authorship contribution statement

Chuen Hon Koh: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Florent Gauvin:** Writing – review & editing, Supervision. **Katrin Schollbach:** Writing – review & editing, Supervision. **H.J.H. Brouwers:** Writing – review & editing, Supervision.

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.

Appendix A. FTIR and TGA on straws

The effect of alkali treatment on straws is further verified using FTIR and TGA, presented in Figure A1. Similar to the previous study on wood wool alkali treatment [4], both 0.5 M and 1.0 M NaOH treatment of straws leads to delignification, resulting in the reduction of characteristic peaks associated with lignin vibrations at 1250 cm^{-1}, C-O ester vibrations peak at 1025 cm^{-1} [60], and aromatic skeletal vibration at 1510 cm^{-1} [61]. Additionally, a significant reduction in peak intensity at 3300 cm^{-1} associated with the OH group [62] suggests disruption of intermolecular hydrogen bonding in cellulose or a decrease in free water content within the treated fibres. The thermogravimetric analysis confirms the delignification of the straws, with untreated straws exhibiting the highest mass loss followed by treated straws, indicating a higher degree of delignification with higher NaOH concentration. The main peak, spanning from 200 to 400°C, corresponds to the decomposition of hemicellulose and cellulose [63], and the lignin components pyrolyzed in the range of 225 and 450°C [64].

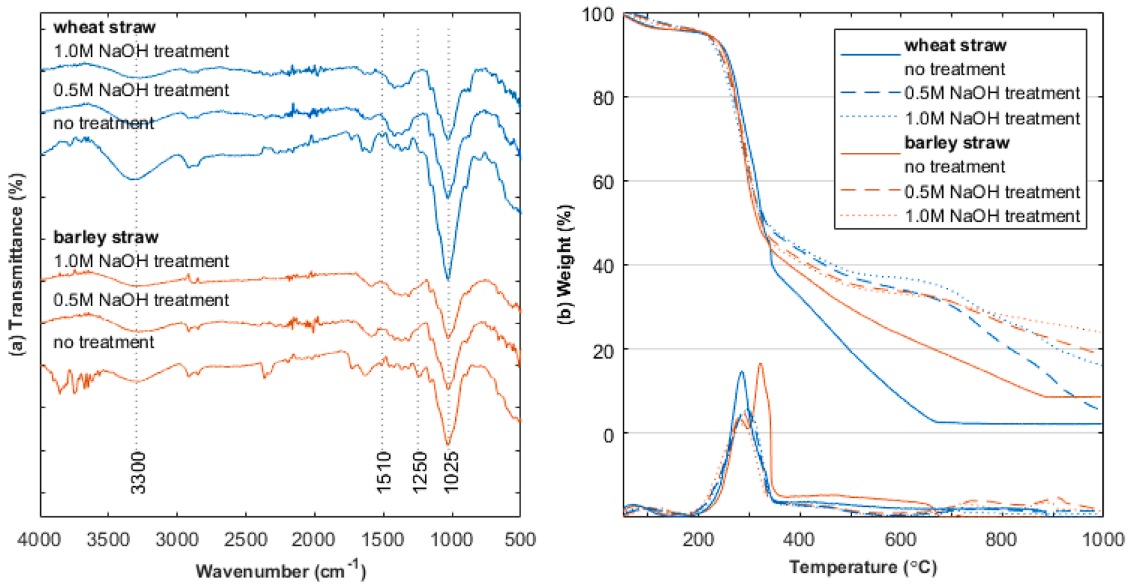

Figure A1. (a) FTIR and (b) TGA of barley and wheat straw samples used in this study

Data Availability

Data will be made available on request.

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