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ORIGINAL PAPER

# Analysis of Biowaste-Based Materials in the Construction Sector: Evaluation of Thermal Behaviour and Life Cycle Assessment (LCA)

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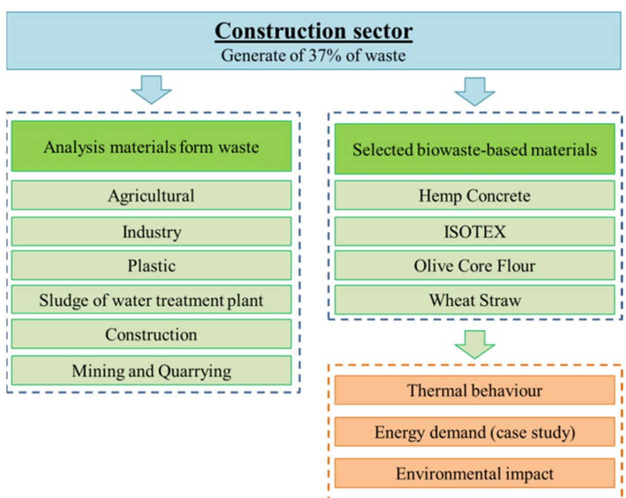
## Abstract
The objective of the work is to evaluate the thermal behaviour and the environmental impact of selected building biowaste-based materials, mainly biomass from agrowaste. An evaluation of the state of the art of the materials used from waste or biomass in the construction of buildings is carried out. The selected building materials are based on data availability: hemp concrete, isotex, bricks with olive core flour (OCF), bricks with wheat straw (WS). Subsequently, thermal behaviour is evaluated as a function of decrement factor, time lag and as an application in the thermal envelope of a building. Finally, a life cycle assessment of each material is carried out, including the calculation of the following indicators: non-renewable energy, cumulative energy demand and global warming potential. Hemp concrete and isotex are the materials with better thermal behaviour (lower decrement factor and greater time lag) like conventional materials, but with lower environmental impact. Regarding bricks, mixtures of 8% OCF and 7%WS generate more stable indoor temperatures than 4% OCF and 3%WS. Compared with conventional materials, building materials with incorporated biomass have better thermal behaviour and allow the construction of buildings with lower life cycle impact.

### Graphical Abstract




**Keywords** Biowaste-based materials · Agrowaste · Thermal behaviour · Energy demand · Life cycle assessment · Sustainable buildings

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## Statement of Novelty

The use of biowaste-based materials in the construction sector should contribute toward buildings with low energy consumption, ensuring adequate thermal comfort. Previous studies provide information about the thermal and structural properties of materials with waste mixtures. This work aims to analyse the thermal behaviour of biowaste-based materials (mainly biomass from agrowaste), apply these materials in the thermal envelope and evaluate the energy consumption of a building through different case studies. This work enables us to compare and select the biowaste-based materials with the best thermal behaviour. In addition, each material is analysed through a life cycle assessment (LCA), which includes the indicators: non-renewable energy (NRE), cumulative energy demand (CED), and global warming potential (GWP).

## Introduction

Reducing energy consumption in buildings is one of the objectives set by the European Union in its roadmap towards a low carbon economy in 2050. To limit the increase in global temperature below 2 °C, $CO_2$ emissions must be reduced by 80–90% by 2050 compared to 1990 [1]. However, because of the Paris Agreement, the member states agreed to increase their efforts and limit temperature increases to 1.5 °C [2]. With the aim of a progressive and irreversible reduction of anthropogenic greenhouse gas emissions, the European Climate Law is published in 2021 (Regulation EU/2021/1119) [3]. The objective of the member states is to achieve climate neutrality by 2050. In addition, it establishes as an intermediate objective, a reduction of greenhouse gas emissions of 55% by the year 2030.

European's Union priority to achieve climate neutrality is based on the reduction of emissions, energy efficiency and, the development of renewable energies. In these three areas, buildings are a strategic sector since they can actively participate in all objectives. Their contribution to the European objectives will not only be based on reducing the energy demand of buildings, but will also contribute through the use of waste-based materials in construction. The use of waste-based materials allows reducing the energy consumption associated with the life cycle (extraction, production, transport and treatment) and, therefore the Global Warming Potential (GWP) associated with the materials. As indicators, Cumulative Energy Demand (CED) allows to evaluate the energy consumed associated with the life cycle of materials, including renewable energies and Non-Renewable Energies (NRE). The use of waste or biomass for the production of biowaste-based materials reduces the greenhouse gas emissions associated with the production of construction materials. These circular and regenerative economy techniques allow the growth of the sector without increasing the consumption of natural resources and reducing greenhouse gas emissions. Reducing the extraction of raw materials contributes to biodiversity conservation and protection and to the improvement of natural capital.

Figure 1 shows the tons of waste generated by activity in the European Union, observing that the construction, mining and quarrying sectors generate the highest amount of waste. In the construction sector, there is an increase in the amount of waste generated, increasing from 30% in 2004 to 37% in 2018 [4], being the sector with the highest increase in waste generation.

The selection of materials with a low-environmental impact in the building design phase can reduce $CO_2$ emissions by 27% [6]. The use of waste-based materials allows the reduction of the embodied energy of buildings (which is the energy used in the manufacture of materials). Taboada et al. calculated the embodied energy by evaluating the design and construction phase of a building. The results showed that the use of recycled materials reduces embodied energy in the manufacture of materials by 53% compared to the use of conventional materials. Including recycled materials and Best Available Techniques (BAT) in the construction sector, embodied energy can be reduced by half [7].

Waste-based materials and BAT use in the construction sector, not only cause a reduction in waste in the sector, but could also generate a reduction in waste in the mining sector. Thus, production of Ordinary Portland Cement

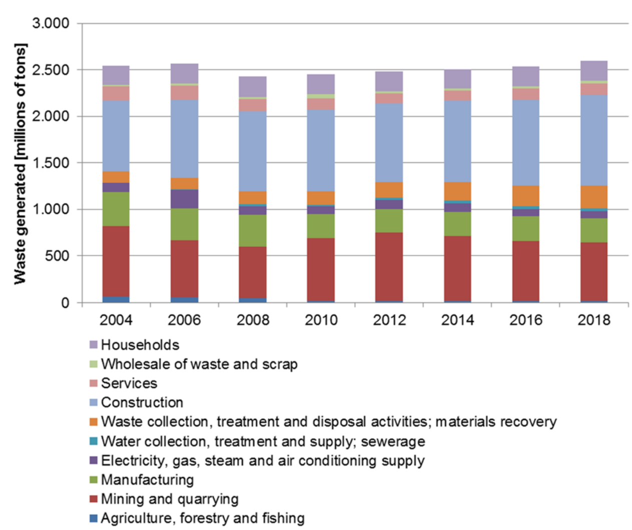


**Fig. 1** Total amount of waste generated in European Union [Data Source Eurostat]

(OPC) accounts for 7% of the world $CO_2$ emissions and it is expected to quadruple in the next 30 years. The use of new formulations in cement production could reduce $CO_2$ emissions and production costs by 50% [8].

The incorporation of waste in construction materials manufacture allows reducing $CO_2$ emissions. The use of recycled materials in the manufacture of concrete such as marble waste [9] or waste metalized plastic fibres and palm oil fuel ash are different examples [10]. Production of sustainable concrete, incorporating recycled materials, does not have to harm the mechanical properties. Thus, the incorporation of 5% of Silica Stone Waste (SSW) powder on concrete improves the tensile and compressive strength by 18% and 10%, due to the production of a material with a lower number of pores and greater density [11].

Thermal insulation produced by natural raw materials requires less energy consumption compared to those that come from artificial raw materials [12]. Agricultural wastes, such as hemp, have been shown to have good thermal and mechanical properties. The use of this type of materials, due to its low cost, improves comfort and therefore leads to both social and economic sustainability [13]. According to Gaujena et al., the thermal insulation of agricultural residues such as hemp, have thermal conductivities between 0.0544 and 0.0594 W/m·K. However, these materials should not be in contact with water. Due to its high-water absorption capacity, this material can increase its weight by 198% and its volume by 40% [12]. The use of agricultural waste in construction materials improves acoustic performance. The use of mortar mixtures with 10% vegetable fibres, such as khorasan wheat chaff, increases the sound absorption average index to 0.38, compared to 0.15 for mortar. This improvement in acoustic performance is produced by obtaining a material with greater porosity and lower density [14].

The waste-based materials used in construction have different origins. Pennachia et al. (2016), analysed the use of urban waste for the building envelope to obtain U-values of 0.25 $W/m^2 \cdot K$. The considered wastes were cardboard tubes, automobile tires, wood pallets, and plastic and glass bottles. The results showed that the use of materials such as glass bottles, tires and wood pallets are more viable economically compared to a traditional structure [15]. The use of ashes generated from the incineration of urban solid waste can be used for the production of alkali-activated cementitious material, whose mechanical properties improve by increasing the dose of sodium silicate [16]. The fly ashes from the incineration can be used in pelletizing processes and be used as aggregates. However, the use of pre-treatments improves the properties of the ashes. Carrying out a wash allows the elimination of soluble salts that can affect the stabilization process and improve mechanical strength [17, 18].

The application of circular and regenerative economy techniques on a large scale would allow an increase in GDP of 0.5% for the European economy in 2030 and the generation of 700,000 jobs [5]. In the case of the construction sector, this can be done by the introduction of waste-based materials, reducing the generation of waste and the consumption of raw materials.

## Analysis of Waste-Based Materials

Waste can be reinjected into the economy as a secondary raw material and become part of the production process. The use of waste allows reducing the consumption of raw materials for the production of construction materials and reducing the environmental impact. As previously shown, there are several types of secondary raw materials that are incorporated into the processes, generating value to the production process. The use of recycled materials is wide and numerous. In this section, a description of the recycled materials currently used in the construction sector is carried out.

### Materials from Agricultural Wastes

Agricultural wastes in the European Union represent 1% of the total (together with forestry and fishing) [4]. However, these residues are generated all over the world and there are numerous studies in which these residues are reused in the production of construction materials.

Agricultural wastes are used mainly as insulating materials since they have thermal insulation very similar to conventional materials; however, they are very susceptible to humidity and biological attacks. This type of waste can be classified into two types: crushed stalks or husks and fibres [19].

One of the most widely used agricultural materials around the world is straw, especially in developing countries. Straw is an organic and easily accessible material, so it is not necessary to transport it long distances [20]. The insulating capacity of this material is known and depends on several factors such as the straw type used, the water content, the density of the bale, the gap between each bale, the density of the coating in the interstices, the orientation of the fibres, the nature and the thickness of the coatings [21]. As an example, the use of straw as bales would allow to achieving thermal transmittance of walls below 0.15 $W/m^2 \cdot K$ [22]. Regarding the use of this biowaste-based material, it is necessary to consider important aspects such as fire resistance. When this type of material is packed, its fire resistance is comparable to conventional construction materials, however; when the straw is dispersed it is highly flammable [20].

Other authors analysed the utilization of another type of agricultural waste. The use of straw fibres (SF) or olive fibres (OF) joined with silicate solution for the formation of insulating panels. Comparing these panels with EPS panels; to achieve U values of 0.27 W/m$^2$·K, higher material thicknesses are needed, but lower annual energy demand is obtained [23]. In other cases, the combination of cork fibres waste with cardboard can be used as reinforcement for the gypsum matrix. Adding 60% cork fibres reduces the thermal conductivity of the plaster from 0.223 to 0.062 W/m·K. By adding cardboard waste to the mixture, thermal conductivity and sound absorption are slightly reduced, but the compressive strength is improved [24].

Sani et al. (2017) studied the impact of introducing agricultural wastes on the thermal and mechanical properties of bricks. In the study, they introduced wheat straw (WS) and olive core flour (OCF). The use of these residues in the elaboration of clay ceramics improves the thermal properties without damaging the mechanical properties and also reduces energy consumption in the manufacturing process. Among the results, they obtained that the use of 4% OCF reduces the thermal conductivity by 16% and in the case of using 8% OCF; it is reduced by 28%. In both cases, mechanical strength remains above industry standards. Furthermore, by adding 3 or 7% of WS, there is a reduction in thermal conductivity of 20 and 30%, respectively. However, in this case, the mechanical strength is lower than the use of OCF [25]. Other authors analysed the use of agricultural waste (such as rice straw, sugarcane bagasse and wheat straw ashes) with the sludge of a water treatment plant (SWTP) to replace 50% of the clay. In these cases, the use of up to 10% of agricultural residues would allow the compression strength to be maintained within quality standards (> 8 MPa), thus reducing the environmental impact and reducing the demand for raw materials [26].

Agricultural wastes can also be incorporated into cement production. Pereira et al. (2020) analysed the properties of coconut fibres to be used in cement matrices. Among the main properties of coconut fibres, the amount of lignin present stands out. Lignin would improve the mechanical properties of cement. Also, due to the low density of the coconut fibres, it would allow producing lighter types/blocks of cement [27]. These improvements in mechanical properties were also found when adding rice husk ash (RHA). Using 15% RHA improves compressive strength by 20% [28]. However, the addition of agricultural residues such as wheat straw (200 g of wheat straw for each 4.4 kg of cement), generates a compound with lower resistance to compression, but better flexural tensile strength [29].

Numerous agricultural wastes can be used for the production of biowaste-based materials, both as thermal insulation and as part of structural elements. Each material must be evaluated individually to know the influence on the thermal and mechanical properties of the resulting compounds. However, the reuse of this waste has great potential to reduce the consumption of raw materials in the manufacture of construction materials.

## Materials from Industry Waste

Vegetable fibres residues from industry can be incorporated into the manufacture of waste-based materials. The food industries generate large amounts of waste that can be reused for the manufacture of construction materials.

Martinez et al. (2012) studied the use of waste generated in the production of beer for the manufacture of bricks. The bagasse residue generated can account for 65–81% of the raw material used. The use of 2.5% bagasse in the manufacture of bricks (fired for 1 h at 950 °C), produces a brick with an apparent density and a resistance to compression similar to that of pure clay. For higher bagasse concentrations, the thermal resistance of the brick increases, but the compressive strength decreases [30].

The sugar cane bagasse ash (SCBA) is generated as a secondary product of the process combustion of the sugar, in alcohol and electricity factories. According to the study carried out by Tonnayopas, the use of 30% SCBA in bricks produced at 1050 °C allows maintaining the quality according to the Thai standard [31].

SCBA is a compound with a high concentration of silica, so it can also be used as an additive for the production of concrete or mortar. The use of 20% ultrafine SCBA in concrete production maintains the same mechanical response as concrete prepared with Portland cement [32–34]. In addition, the use of 5% SCBA improves the durability and impact resistance of concrete. Zareei et al. (2018) found in the production of materials, the demand for water increases with the amount of SCBA due to porosity and irregularity [35]. Waste from the textile industry can also be used for the production of waste-based materials. Studies carried out with textile waste show that they can be used as reinforcement in cement compounds for non-structural elements, obtaining an improvement in toughness and the ability to withstand post-cracking stress. Thus, in the case of reinforced mortars with textile fibres, it is possible to obtain a flexural strength of 15.5 MPa and a toughness of 9.7 kJ/m$^2$ [37, 38].

## Materials from the Sludge of Water Treatment Plant (SWTP)

Sludge from water treatment plant (SWPT) has a heterogeneous composition due to the different input sources. On the one hand, the organic matter content is between 60 and 80% in dry solids. On the other hand, the inorganic content of these residues ($SiO_2$, CaO, $Al_2O_3$, $Fe_2O_3$, MgO and $P_2O_5$) makes their use of special interest [39].

One of the potential uses of SWPT is for the production of ceramic tiles or bricks, even in combination with agricultural wastes [26]. Amin et al. (2018) evaluated the addition of dried sewage sludge in percentages between 5 and 35% for the production of ceramic tiles. The maximum amount of added sludge for the production of 7,5 mm tiles was 10% for tiles fired at 1150 °C (for water absorption > 10%) and 7% (for water absorption < 10%) [36]. According to the review made by Chang et al. (2020), in the use of SWPT in the manufacture of ceramic materials, the increase in sewage sludge increases water absorption and porosity. In order not to affect long-term performance, the addition of sludge should be limited to 20% [39].

The generated sludge (wet or dry) can be used for the production of concrete, mixed with up to 15% of the weight in cement. This proportion allows producing concrete without causing a significant reduction in compressive strength [40]. A higher contribution of sludge considerably reduces compressive strength [39, 40]. However, when the sludge is previously incinerated, up to 25% of the sewage sludge ash can be incorporated without affecting the compressive strength. The optimal mix is between 10 and 20% [41].

### Materials from Plastic Waste

The production of plastic in the last decades has increased exponentially, reaching 322 million tons worldwide in 2015. The fate of plastics is distributed as follows: 39% are incinerated; 30% are recycled, and 31% are buried [42]. The generation of plastic waste is an environmental problem that generates health problems, water pollution and soil contamination.

Plastic waste such as bottles, already mentioned in this paper's introduction, can become a sustainable and more economical proposal for the construction of thermal envelopes with U values of 0.25 $W/m^2·K$ [15]. Envelopes made with air-filled plastic bottles bonded with mortar have higher thermal resistance than traditional cement blocks, so they can be used as building units for partitions [43]. Plastic waste can also be used in the form of fibres. The use of fibres in concrete mixtures (0–0.5%) reduces the resistance to compression; however, it increases the tensile strength, so the material obtained can be used on industrial floors or pavements [45]. Recycled nylon fibres from fishing nets is another example of waste used as reinforcement for cementitious mortars. These fibres can improve tensile strength by 35% and obtain a mortar with tenacity 13 times higher than an unreinforced mortar [44].

Various studies analyse the introduction of plastic waste in combination with other types of waste. Mohammadhosseini et al. (2018) have demonstrated that Waste Metallized Plastic (WMP) fibres have a good chance of being used as fibrous materials to improve the durability of concrete. The incorporation of Palm Oil Fuel Ash (POFA) into the WMP fibres increased the air content of the concrete mixes. Additionally, water absorption and sorptivity were reduced with volume fractions up to 0.75% for both Ordinary Portland Cement (OPC) and POFA-based. Therefore, the production of durable and sustainable concrete is possible using WMP fibres [10]. The addition of WMP produces higher tensile and flexural strength, but a reduction in compressive strength. The highest tensile and flexural strength is obtained with 0.5% WMP fibres for both an OPC-based composite and 20% POFA (replacing OPC) [46].

### Materials from Construction Waste

In 2018, in the European Union, the construction sector generated 973 million tons of waste [4]. Although much of the waste generated in the sector (concrete, brick, gypsum, wood, glass, metal, plastics, etc.) could be recycled, they end up in landfills. The reuse of Concrete and Demolition Waste (CDW) in the construction sector has become crucial to contain a large amount of waste generated and also as a form of sustainability.

Silgado et al. (2018) analysed the environmental and economic impacts in the production of structural concrete. The use of recycled cement aggregates and recycled gypsum cement to produce structural concrete allows a cleaner production of concrete, causing a reduction in environmental impact and economic savings [47]. The use of Fine Recycled Concrete Aggregates (FRCA) have better resistance to compression than those made with natural sand; however, the resistance to compression decreases with increasing the amount of FRCA. In addition, water consumption when using recycled sand is higher than in conventional mortars [48]. Similar results have been obtained using recycled aggregates (RCA) from the demolition of civil buildings. Environmental impact is reduced by increasing the amount of RCA and compression strength is maintained for RCA mixes up to 70% [49].

Ossa et al. (2016) analysed the use of CDW for the construction of urban roads. Up to 20% of CDW could be reused while maintaining properties similar to conventional asphalt [50].

### Materials from Mining and Quarrying Waste

Another waste that can be reused for the production of waste-based materials are those that come from the mining and quarrying sectors, such as marble, granite or ceramics.

In the marble treatment process (processing, cutting and polishing), 20–35% of the original marble block is wasted. These wastes are harmful to health and cause a significant environmental impact on water, soil and air. There are several studies about marble residues in the production of concrete, brick and polymeric materials that show that these residues can bring numerous benefits when used in the manufacture of construction materials [9].

Khyaliya et al. (2017) analysed the properties of mortar when fine marble residues are added instead of sand. They concluded that adding 25 to 50% reduces water requirements and improves mechanical properties and durability. For mixtures with 50%, the maximum compressive strength and the minimum water absorption are obtained; however, with mixtures of 25% greater durability and stability are guaranteed [51]. Regarding concrete production, 10% of Portland cement could be replaced by marble slurry. With this mixture, a compressive strength greater than 40 MPa and a flexural strength greater than 6 MPa at 28 days are guaranteed [52]. Also, the use of marble waste as an inert material can be used for the production of self-compacting concrete [53].

Like marble dust, granite dust can also be used as a fine aggregate in mortars, observing similar behaviours. Fine aggregate in cement mortar mixtures with mixtures of 30 and 40%, a reduction in water requirements and an increase in compressive strength are observed [54].

In the production of ceramic tiles, residues are also produced during the final polishing process. According to the study carried out by El-Dieb et al. (2018), Ceramic Waste Powders (CWD), due to their similar characteristics to cement (including more than 85% $SiO_2$ and $Al_2O_3$), have the potential to be used as an alternative ingredient in concrete. The compressive strength at 28 days, shows an increase of 4% for mixtures up to 20%. However, all mixtures with CWP (up to 40%) showed good development of compressive strength at 90 days, reaching the minimum compressive strength [55]. Other studies establish a substitution of 15% of CWP as a filling material in substitution of cement to produce self-consolidating concretes. With this percentage, a drastic reduction in strength is not observed in hardened concrete [56].

There is also the possibility of reusing mineral waste in the manufacture of different products. The kaolin processing industry generates a large amount of waste. There is also the possibility of reusing mineral waste in the manufacture of different products, such as paints. The kaolin processing industry generates a large amount of waste. The geotint, based on the kaolin residue, presented characteristics similar to those observed in industrialized paints: coating, fast drying and resistance, with good adhesion to the surface. Kaolin residues turned out to be good materials in the composition of soil-based paint, being a sustainable and economical alternative [57].

## Objectives

The objective of this work is to evaluate the introduction of biowaste-based materials (from agricultural waste) in the construction sector considering their thermal behaviour and the environmental impact to reduce waste generation and the consumption of natural resources.

Thermal behaviour is evaluated by analyzing the evolution of temperature (decrement factor and time lag), to evaluate which biowaste-based materials provide a more stable temperature. In this way, it is possible to select those biowaste-based materials based on the thermal comfort generated which allow low energy consumption in buildings.

The environmental impact is evaluated using the following LCA indicators: non-renewable energy (NRE), cumulative energy demand (CED) and the global warming potential (GWP), which allow selecting biowaste-based materials with lower environmental impact than conventional materials.

## Materials and Methods

### Selection of Biowaste-Based Materials

The main criterion for the selection of biowaste-based materials is the availability of data on their thermal properties. Having the database is essential to be able to carry out the simulations properly. The selected materials belong to the group of agricultural waste. Those waste types are widely used throughout the world and they are materials with similar behaviours to conventional thermal insulation.

#### Hemp Concrete

Hemp concrete is made from hemp mixed with lime and water. It is an ecological, energy-efficient and long-lasting material. It also has qualities of thermal insulation, is non-toxic and resistant to fire and pests. In addition to being more sustainable, it is considered zero carbon as it stores active carbon from the atmosphere [58].

The thermal properties of hemp concrete allow it to be used as an insulating material, since they have a conductivity between 0.05 and 0.16 W/(m·K) for a density between 220 and 550 kg/m$^3$, the specific heat varies depending on the density of the compound oscillating between 900 and 4700 J/(kg·K) [59]. For the analysis, a thermal conductivity of 0.071 W/(m·K), a density of 340 kg/m$^3$ and a heat capacity of 1000 J/(kg·K) are used.

This material is introduced in scenario 1. The metallic structure is maintained and 15 cm of hemp concrete is included. In addition, 4 cm of expanded cork and 1 cm of plasterboard are included to close the structure.

#### Isotex

Isotex is a material made from pieces of wood that can be sawdust or discarded pallets. The use of waste makes it more than an ecological material, since it allows to value waste generated in the environment. The material has thermal and acoustic insulation qualities and, like hemp concrete, removes activated carbon from the atmosphere [60].

The thermal characteristics are different from hemp concrete. It has a conductivity of 0.105 W/(m·K), but with a higher thermal capacity of 1500 J/(kg·K).

Scenario 2 includes 25 cm of Isotex to close the structure. It also includes 4 cm of expanded cork, 1 cm of plasterboard and final paint. The main alterations are in the wall, and the only change in the ceiling is the replacement of the insulating material rock wool by an expanded cork (4 cm).

### Olive Core Flour (OCF)

Scenarios 3 and 4 are the combination of the structural elements of the house in the conventional style but including bricks made with olive core flour (OCF) residues. Two variants are analysed, scenario 3 is composed of bricks with 4% OCF and scenario 4 is use bricks with 8% OCF.

Different authors studied the thermal and mechanical properties of these compounds. The thermal conductivity for bricks with 4 and 8% OCF have a value of 0.42 and 0.6 W/(m·K) [25, 61], and the density of both bricks varies between 1760 and 1586 kg/m$^3$ [61] respectively.

Heat capacity is determined by the relationship between the specific heat of OCB (1750 J/(kg·K)) [25] and of conventional brick (545 J/(kg·K)) [62]. Therefore, the specific heat for 4 and 8% OCF bricks is 590 and 640 J/(kg·K).

Scenarios 3 and 4 include 15 cm of 4 and 8% OCF brick with 4 cm of expanded cork insulation.

### Wheat Straw (WS)

The latest scenarios (5 and 6) consist of introducing ceramic bricks made with 3 and 7% wheat straw (WS).

The thermal conductivity of the bricks is 0.40 and 0.35 W/(m·K) [25] with a density of 1740 and 1571 kg/m$^3$ [61] respectively.

The specific heat for the WS considered was 2181 J/(kg·°C) [25] and the value considered for the conventional brick was 545 J/(kg·K) [62]. Therefore, the specific heat for 3 and 7% WS bricks is 595 and 660 J/(kg·K).

Scenarios 5 and 6 include 15 cm of 3 and 7% WS brick with 4 cm of expanded cork insulation.

### Summary of Biowaste-Based Materials

The materials described in the previous sections are part of the thermal envelope of the building. Table 1 summarizes the properties of the selected materials.

**Table 1** Summary of biowaste-based materials properties

| Scenario | Materials | Conductivity [W/(m·K)] | Density [kg/m$^3$] | Heat capacity [J/(kg·K)] |
|---|---|---|---|---|
| 1 | Hemp concrete | 0.071 | 340 | 1000 |
| 2 | ISOTEX | 0.104 | 510 | 1500 |
| 3 | 4% OCF | 0.42 | 1760 | 590 |
| 4 | 8% OCF | 0.35 | 1586 | 640 |
| 5 | 3% WS | 0.40 | 1740 | 595 |
| 6 | 7% WS | 0.35 | 1571 | 660 |

## Analysis of the Thermal Behaviour

For the study of the thermal behaviour of the materials, the decrement factor and time lag generated by a 20 cm monolayer wall are evaluated. The results are obtained using the analogy between the electric field and the thermal field, through the model developed by Vilaboa et al. [63]. The system is subjected to a sinusoidal disturbance with a maximum temperature of 40 °C and a minimum of 20 °C during a period of 24 h. Through the response of the system, the decrement factor and the time lag are obtained.

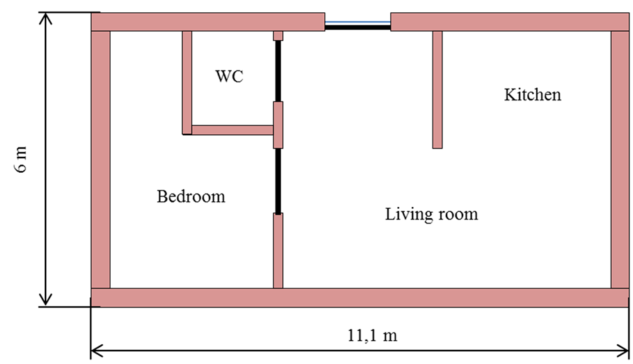


**Fig. 2** Drawing of the building to study

## Analysis of Energy Demand

### Case Study

In order to evaluate the introduction of materials from waste in the energy consumption of a building, a prefabricated house is taken as a reference. This type of construction is characterized by its low cost and by generating less waste during construction. The distribution and size of the house are considered in such a way that it allows two people to live there. Figure 2 shows a drawing of the building, which has a surface of 6 × 11.1 m, so it has a constructed area of 66.6 m$^2$.

The floor consists of a reinforced concrete slab with cooperating sheet metal as permanent formwork, 8 cm thick extruded polystyrene, regularization mortar and final coating (floating flooring or ceramic coating).

The roof is composed of an 8 cm thick sandwich panel and a double layer of crossed asphalt fabric. Cover closure on 12 mm thick OSB boards, 4 cm thick rock wool and finally plasterboard (including interior paint).

The exterior walls are made of granite tiles, aquapanel system with baked cement board application, waterproof and fire-resistant. It includes a 2 cm thick air box, 8 cm thick extruded polystyrene, 4 cm thick rock wool and a plasterboard system including interior paint (or ceramic coating on the toilet).

The materials used for this modelling are listed in Table 2 as well as the values necessary for their application in the Lesosai software, which include the values of thermal conductivity (W/m·K), density (kg/m$^3$), and specific heat (J/kg·K). These values have been extracted from the software itself (Lesosai), which includes a database, or from the manufacturer.

The biowaste-based materials described in previous section, are included in the thermal envelope, establishing 6 different enclosure scenarios. The table summarizes the enclosures for each scenario under study. Only the walls and roof are described, while the floor is the same in all cases. The thermal transmittance of each wall or roof is shown.

The climatic conditions considered for the evaluation of the energy demand of the dwelling correspond to the municipality of Porto (Portugal). This region has a Mediterranean climate with oceanic influence (Csb) according to the Köppen climate classification.

### Simulation Software

The simulation software used is Lesosai which allows studying the efficiency of buildings with different materials. Lesosai allows obtaining the heating demand of the buildings applying the EN-ISO 13790 and SIA380/1. For this, the software considers the heat transfer by transmission and ventilation, the internal gains, the solar contributions and the energy accumulation.

The software has been tested for compliance with the SIA380/1 standard and allows obtaining the MINERGIE label.

## Life Cycle Assessment Data

The proposal of the study is to carry out an environmental comparison of the production stage of the biowaste-based materials described, without considering the extraction of materials or transportation.

The data for the life cycle assessment comes from Lesosai software, which uses the KBOB database from the Group for Construction and Property Services. The database has the following indicators for the production of construction materials:

- NRE: Non-renewable energy. Indicates the amount of non-renewable energy used to manufacture a certain product, measured in MJ (megajoules).
- CED: Cumulative Energy Demand. Indicates the amount of total energy (renewable and non-renewable) that was used to manufacture a certain product, measured in MJ (megajoules).
- GWP: global warming potential. It is the rate of greenhouse effect ($CO_2$, $N_2O$, $CH_4$, etc.), measured in kg $CO_2$-eq.

**Table 2** Original building materials description

| Constructive Element | Materials | Conductivity [W/(m·K)] | Density [kg/m3] | Heat capacity [J/(kg·K)] |
|---|---|---|---|---|
| Floor | Reinforce concrete | 1.8 | 2400 | 1100 |
| | Extruded polystyrene | 0.036 | 25 | 1400 |
| | Cement mortar | 1 | 1700 | 1000 |
| | Parquet Floor | 0.14 | 900 | 2200 |
| Wall | Granite | 2.8 | 2600 | 1000 |
| | Aquapanel Knauf | 3 | 1156 | 1500 |
| | Extruded Polyestyrene (XPS) | 0.035 | 30 | 1404 |
| | Rock Wool, 100 kg/m$^3$ | 0.04 | 100 | 600 |
| | Gypsum plasterboard | 0.21 | 850 | 800 |
| | Acrylpaint | 0.2 | 1050 | 1400 |
| Roof | Swisspor PUR Premium | 0.021 | 30 | 1404 |
| | Steel | 60 | 7850 | 500 |
| | Bitumen sealing | 0.17 | 1100 | 1800 |
| | OSB board, PF-glued, for exterior | 0.13 | 600 | 2160 |
| | Rock Wool, 100 kg/m$^3$ | 0.04 | 100 | 600 |
| | Gypsum plasterboard | 0.21 | 850 | 800 |
| | Acrylpaint | 0.2 | 1050 | 1400 |

Materials not included in the KBOB database will be obtained from the technical specifications of manufacturers or from a bibliographic review.

The functional unit considered for carrying out the study is 1 kg of each type of material (hemp concrete, isotex, 4 and 8% OCF and 3 and 7% of WS). For the analysis of the selected materials, the same mass (1 kg) is considered, so the volume will be different. For bricks with OCF or WS, both have similar density and heat capacity. However, they will not be comparable to hemp concrete or isotex, which have lower densities and higher heat capacity than OCF and WS bricks. Materials are evaluated as part of the thermal envelope as insulting materials.

## Development and Presentation of Results

### Analysis of the Thermal Behaviour

In Fig. 3, the response of the different biowaste-based materials to sinusoidal disturbance is shown. It is observed that all materials generate a time lag between 6.7 and 10 h. The material with the worst thermal response is brick with 4% OCF, generating a wave with a greater oscillation (4.9 °C) and a lower time lag (6.72 h). Conversely, hemp concrete and Isotex produce a wave with a low oscillation of 1.3 and 0.6 °C and a time lag of 9 h.

In Fig. 4, the results of the decrement factor and time lag for each material are shown. Comparing results for biowaste-based materials and conventional materials, better thermal properties are obtained for the first. This is because the introduction of residues in the manufacture of materials makes them have a higher specific heat, so they have a greater capacity to accumulate heat.

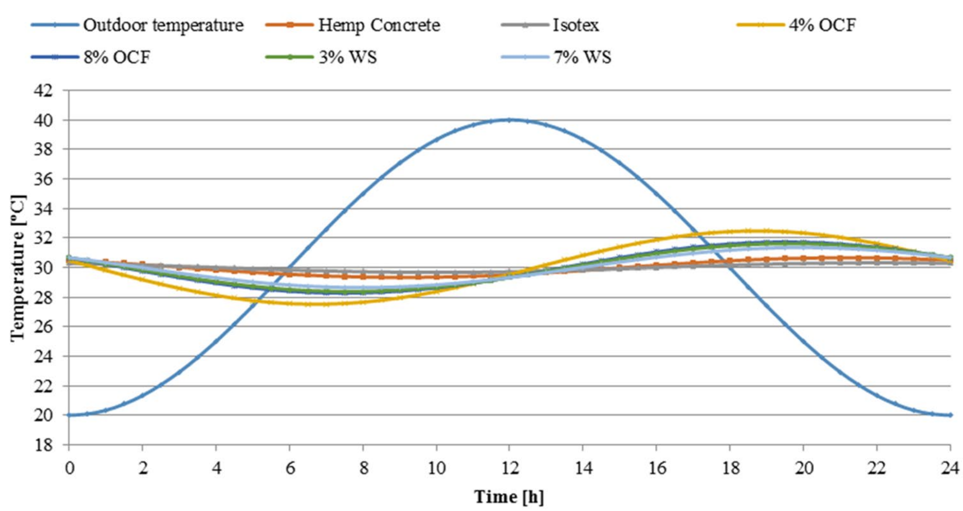


**Fig. 3** Representation of the response in the inner surface of different biowaste-based materials with a 20 cm thickness when the system is perturbed from a sine wave

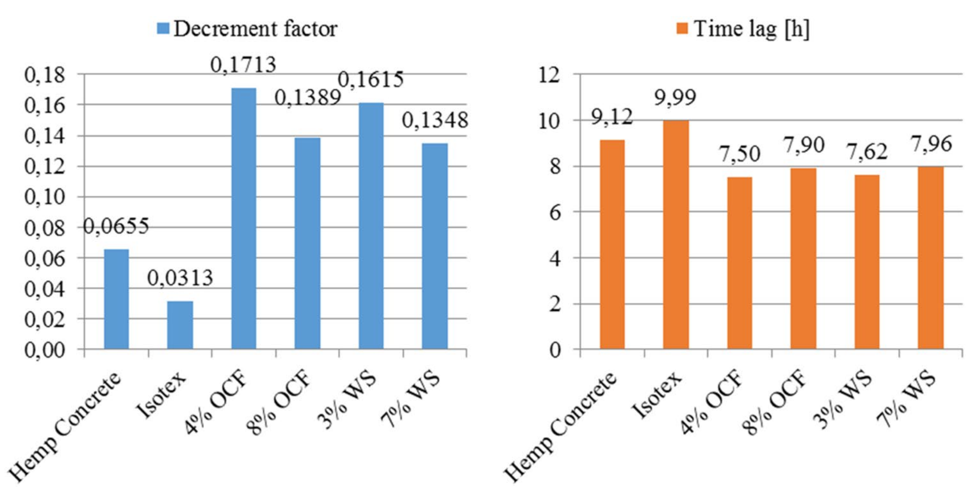


**Fig. 4** Decrement factor and time lag for biowaste-based materials with 20 cm thickness

Comparing conventional concrete with hemp concrete, it is observed that the thermal properties are very different. The decrement factor for hemp concrete has a value of 0.0655, while for conventional concrete the value is 0.6172. This is because hemp concrete has a low thermal conductivity (0.71 W/(m·K)) compared to concrete (2.5 W/(m·K)). However, the function of these materials is not comparable from a structural point of view, since hemp concrete does not have the compressive strength and tensile strength that conventional concrete has.

In the case of bricks, it is observed that the addition of OCF or WS reduces the conductivity of the material, otherwise, a reduction in density and heating capacity is obtained. However, the introduction of recycled materials produces a more stable thermal response. The decrease factor for conventional bricks is 0.2952, while the decrement factor is reduced by adding any of the residues. The lowest decrement factor has been obtained with 7% WS, reaching a value of 0.1348.

## Analysis of Energy Demand for Different Case Studies

The energy efficiency of the prefabricated house was analysed with Lesosai software. To carry out the simulation, the enclosures of the scenario are described in Table 3. The materials properties are already included in the software database. Those materials that are not in the database are added manually.

First, scenario 0 (base case) is analysed, which is the starting case. Figure 5 shows the Sankey diagram of the

**Table 3** Summary of the cases to study to be analysed using Lesosai

| Scenario | Constructive Element | Thermal Transmittance [W/($m^2$·K)] | Materials |
|---|---|---|---|
| 0 (base case) | Wall | 0.2705 | 1.5 cm Granite + 1.25 Aquapanel Knauf + 8 cm XPS + 4 cm Rock Wool 100 kg/$m^3$ + 2.6 Gypsum plasterboard + 0.02 Acrylpaint |
| | Roof | 0.1953 | 8 cm Swisspor PUR Premium + 1 cm Steel + 0.01 cm Bitumen sealing + 1.2 cm OSB board + 4 cm Rock Wool 100 kg/$m^3$ 1 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| 1 (Hemp Concrete) | Wall | 0.3002 | 15 cm Hemp Concrete + 4 cm Expanded cork panels Growancork + 2.6 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| | Roof | 0.1953 | 8 cm Swisspor PUR Premium + 1 cm Steel + 0.01 cm Bitumen sealing + 1.2 cm OSB board + 4 cm Expanded cork panels Growancork + 1 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| 2 (Isotex) | Wall | 0.2761 | 25 cm ISOTEX + 4 cm Expanded cork panels Growancork + 2.6 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| | Roof | 0.1953 | 8 cm Swisspor PUR Premium + 1 cm Steel + 0.01 cm Bitumen sealing + 1.2 cm OSB board + 4 cm Expanded cork panels Growancork + 1 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| 3 (4% OCF) | Wall | 0.6064 | 15 cm Brick OCF 4% + 4 cm Expanded cork panels Growancork + 0.5 cm cement mortar + 1 Gypsum plasterboard + 0,02 Acrylpaint |
| | Roof | 0.1953 | 8 cm Swisspor PUR Premium + 1 cm Steel + 0.01 cm Bitumen sealing + 1.2 cm OSB board + 4 cm Expanded cork panels Growancork + 1 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| 4 (8% OCF) | Wall | 0.6322 | 15 cm Brick OCF 8% + 4 cm Expanded cork panels Growancork + 0.5 cm cement mortar + 1 Gypsum plasterboard + 0.02 Acrylpaint |
| | Roof | 0.1953 | 8 cm Swisspor PUR Premium + 1 cm Steel + 0.01 cm Bitumen sealing + 1.2 cm OSB board + 4 cm Expanded cork panels Growancork + 1 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| 5 (3% WS) | Wall | 0.6251 | 15 cm Brick WS 3% + 4 cm Expanded cork panels Growancork + 0.5 cm cement mortar + 1 cm Gypsum plasterboard + 0.02 Acrylpaint |
| | Roof | 0.1953 | 8 cm Swisspor PUR Premium + 1 cm Steel + 0.01 cm Bitumen sealing + 1.2 cm OSB board + 4 cm Expanded cork panels Growancork + 1 cm Gypsum plasterboard + 0.02 cm Acrylpaint |
| 6 (7% WS) | Wall | 0.6003 | 15 cm Brick WS 7% + 4 cm Expanded cork panels Growancork + 0.5 cm cement mortar + 1 Gypsum plasterboard + 0.02 cm Acrylpaint |
| | Roof | 0.1953 | 8 cm Swisspor PUR Premium + 1 cm Steel + 0.01 cm Bitumen sealing + 1.2 cm OSB board + 4 cm Expanded cork panels Growancork + 1 cm Gypsum plasterboard + 0.02 cm Acrylpaint |

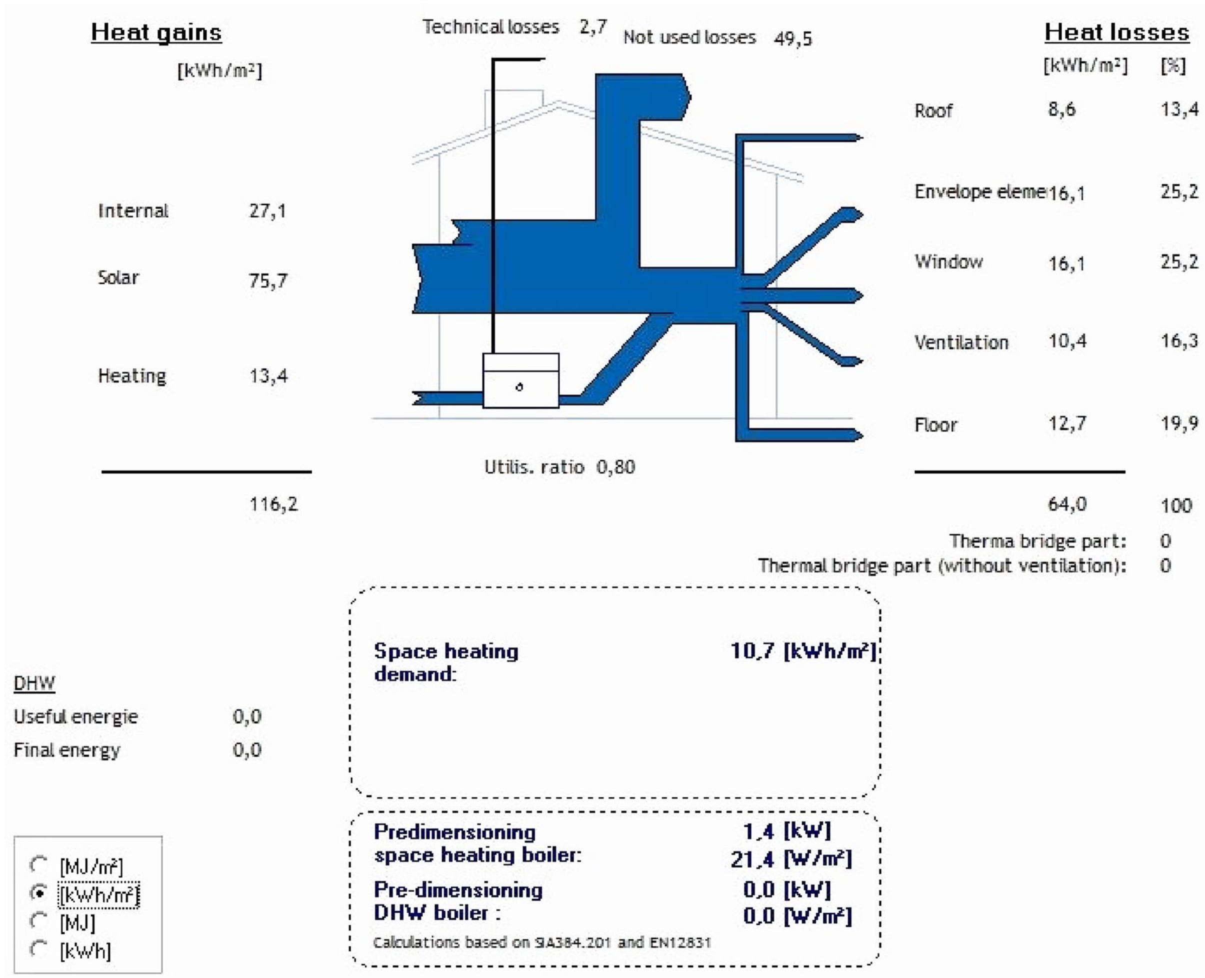


**Fig. 5** Sankey diagram for scenario 0 (base case)

building. Sankey diagram is provided by the Lesosai software. The annual energy consumption necessary to heat or cool the home is 10.7 kWh/m$^2$ and requires an installed power of 1.4 kW.

With the initial configuration, the energy losses are 64.0 kWh/m$^2$. It should be noted that 16.1% (25.2 kWh/m$^2$) of the losses occur through the envelope and 8.6% through the roof (13.4 kWh/m$^2$). For the other scenarios, the composition of the envelope and roof is varied, while the properties of windows, floor and ventilation remain constant.

To maintain the comfort temperature, the software calculates the energy contribution of the boiler (13.4 kWh/m$^2$) and takes into account the internal gains (27.1 kWh/m$^2$) and the solar inputs (75.7 kWh/m$^2$). Therefore, by modifying the properties of the enclosure, an increase in air conditioning consumption and therefore the installed power increase is caused.

Figures 6 and 7 show the Sankey diagram in the case of use hemp concrete (scenario 1) and isotex (scenario 2). Both cases have similar behaviour with an annual energy consumption of 11.0 y 10.9 kWh/m$^2$. The difference concerning the original scenario (base case) is due to energy losses through the envelope.

On the roof, rock wool is replaced by expanded cork panels, however, as both materials have the same conductivity (0.04 W/m·K), the thermal transmittance (0.1953 W/(m$^2$·K)) is not altered. However, the compositions of the walls are different and their transmittance is higher than for scenario 0, so the losses through the walls are greater. Therefore to maintain the comfort temperature, the boiler must provide greater energy.

As can be seen in both figures, the highest percentage of energy losses occurs through the enclosures. The losses through the roof, walls and floor of the building are 59.7 and 58.7% of the total, for scenarios 1 and 2 respectively.

Figures 8 and 9 show Sankey diagrams in the case of using bricks with 4 and 8% of olive core flour (OCF). In both cases, an increase in annual energy consumption is observed

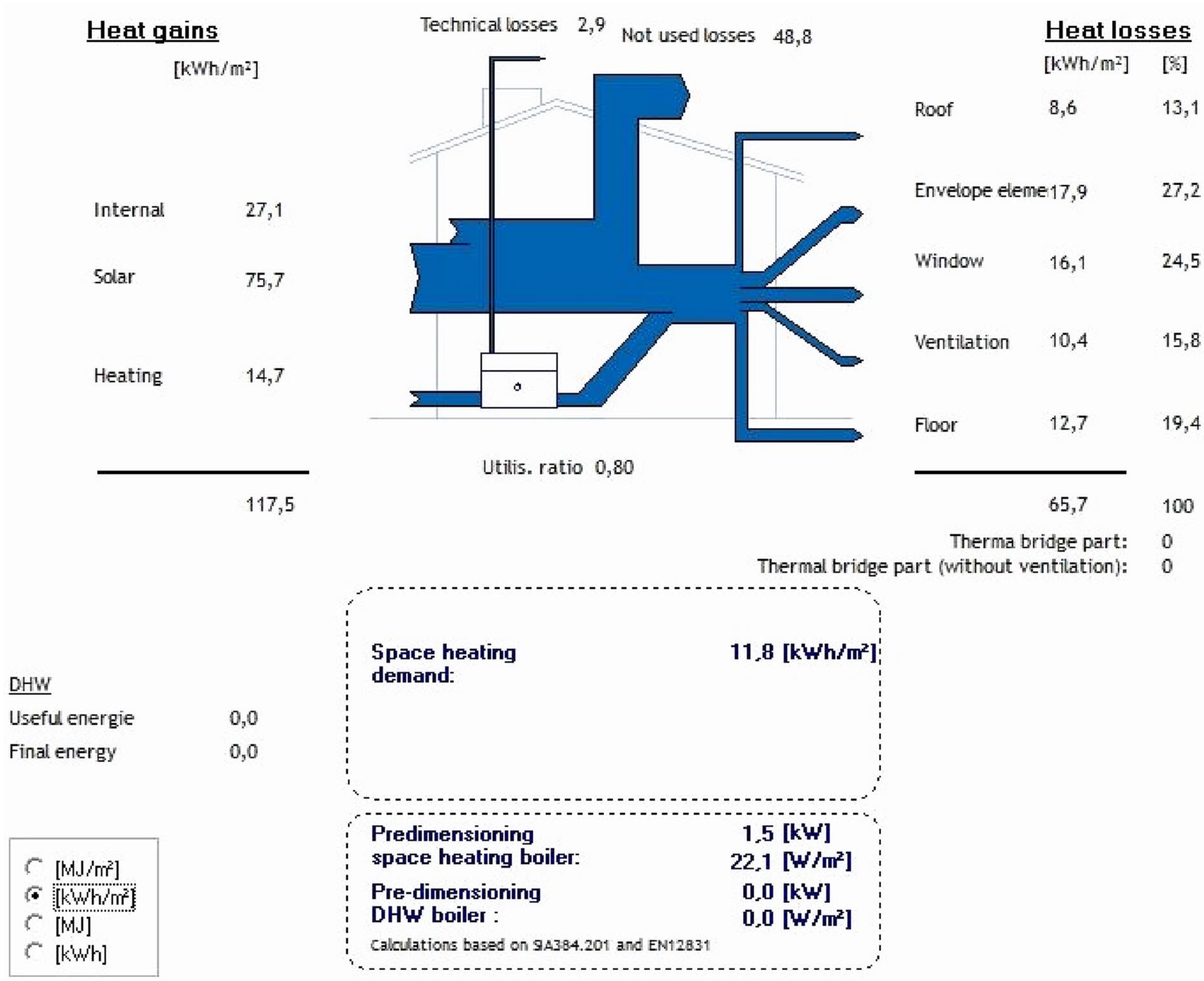


**Fig. 6** Sankey diagram scenario 1 (hemp concrete)

concerning the original and scenarios 1 and 2, having a value of 25.7 and 24.5 kWh/m$^2$. In these cases, it is necessary a boiler of 2.1 and 2.0 kW of power.

The high thermal conductivity of OCF bricks allows a greater heat flow through the walls, causing greater energy losses by conduction. Thus, for scenarios 3 and 4, the energy losses through the roof, walls and floors account for 69.0 and 68.3% of the total losses. Due to this, having a boiler with a higher power to maintain the comfort temperature is necessary.

Finally, Sankey diagrams are shown for scenarios 5 and 6 (Figs. 10 and 11) which use bricks with wheat straw (WS) mixtures. The results show energy consumption values similar to scenarios 3 and 4 (OCF bricks), because the used materials have similar thermal characteristics.

Annual energy consumption for scenarios 5 and 6 is 25.4 and 24.3 kWh/m$^2$, with boiler powers of 2.1 and 2.0 kW, respectively. The percentage of energy losses for both scenarios across the entire envelope is 68.8 and 68.2%.

The results obtained after performing the 6 simulations are summarized in Table 4. The table shows heating demand, boiler power, total energy inputs and total energy losses.

The scenario that requires the lowest annual energy consumption is the base case (scenario 0) that includes 8 cm of XPS and 4 cm of rock wool. The annual energy consumption for the original scenario is 10.7 kWh/m$^2$. The second-best result has been obtained with scenario 2. In this case, an annual consumption of 10.9 kWh/m$^2$ is obtained with a facade composition of 25 cm of Isotex (wood-cement block) and with 4 cm of insulating material of expanded cork. Scenario 1 has the third-best performance with an annual consumption of 11.8 kWh/m$^2$ and a facade composed of 15 cm of hemp concrete and 4 cm of expanded cork insulating element.

In both cases, the installed power of the boiler would be between 1.4 and 1.5 kW, so very similar results are obtained with the three scenarios. The difference between these three scenarios is small, with a consumption variation between 0.2 kWh/m$^2$ and 1.1 kWh/m$^2$ per year, taking into account that

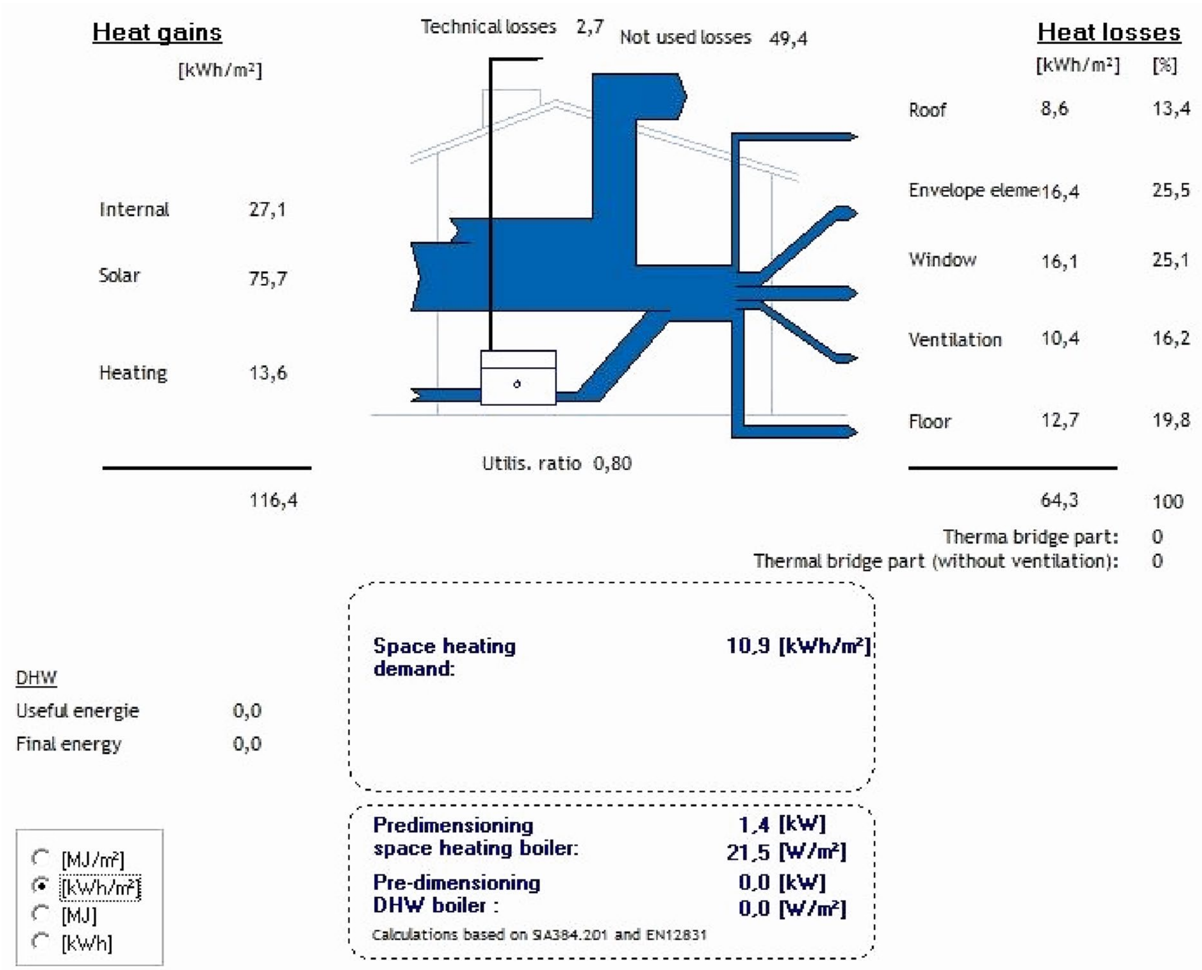


**Fig. 7** Sankey diagram for scenario 2 (isotex)

the base case (scenario 0) has a larger insulating element, which would be extruded polystyrene (XPS) and rock wool.

The cases understudy with the highest energy consumption correspond to scenarios 3, 4, 5 and 6, all of them with a difference greater than the previous ones. Scenarios from 4 to 6 have similar compositions; the walls are made up of 15 cm of brick and 4 cm of insulation with expanded cork. The difference between the scenarios is found in the composition of the bricks. Scenario 6, with composite brick with 7% WS, presents the best performance, with an annual energy consumption of 24.3 kWh/m$^2$. Subsequently, the scenario with the best thermal performance is 4, with a composite brick with 8% OCF, with an annual consumption of 24.5 kWh/m$^2$. Finally, and with higher energy consumption, there are scenarios 3 and 5, which use brick with 4% OCF and 3% WS, which have an annual energy consumption of 25.7 and 25.4 kWh/m$^2$ respectively.

Based on the results obtained, it is observed that the ceramic bricks that use a higher percentage of biomass increases the thermal resistance of the wall and therefore reduces energy losses by conduction. Increasing the percentage of biomass in bricks, generates a reduction in installed power of 0.1 kW, with a reduction in annual energy consumption of 2.2% for brick with OCF and 1.7% for brick with WS.

## Environmental Impact Analysis

In buildings, two different energy consumptions can be considered. Firstly, direct energy consumption in energy maintenance, and secondly, the energy consumed for the production of materials, construction and demolition. Balubaid et al. (2014) define embodied energy as that energy used to produce materials and the construction of the building [64]. However, a more complete definition of embodied energy includes the total energy used in the construction, maintenance and demolition of the building [65].

To assess the environmental impact of the different materials used in the models, the previous indicators (NRE,

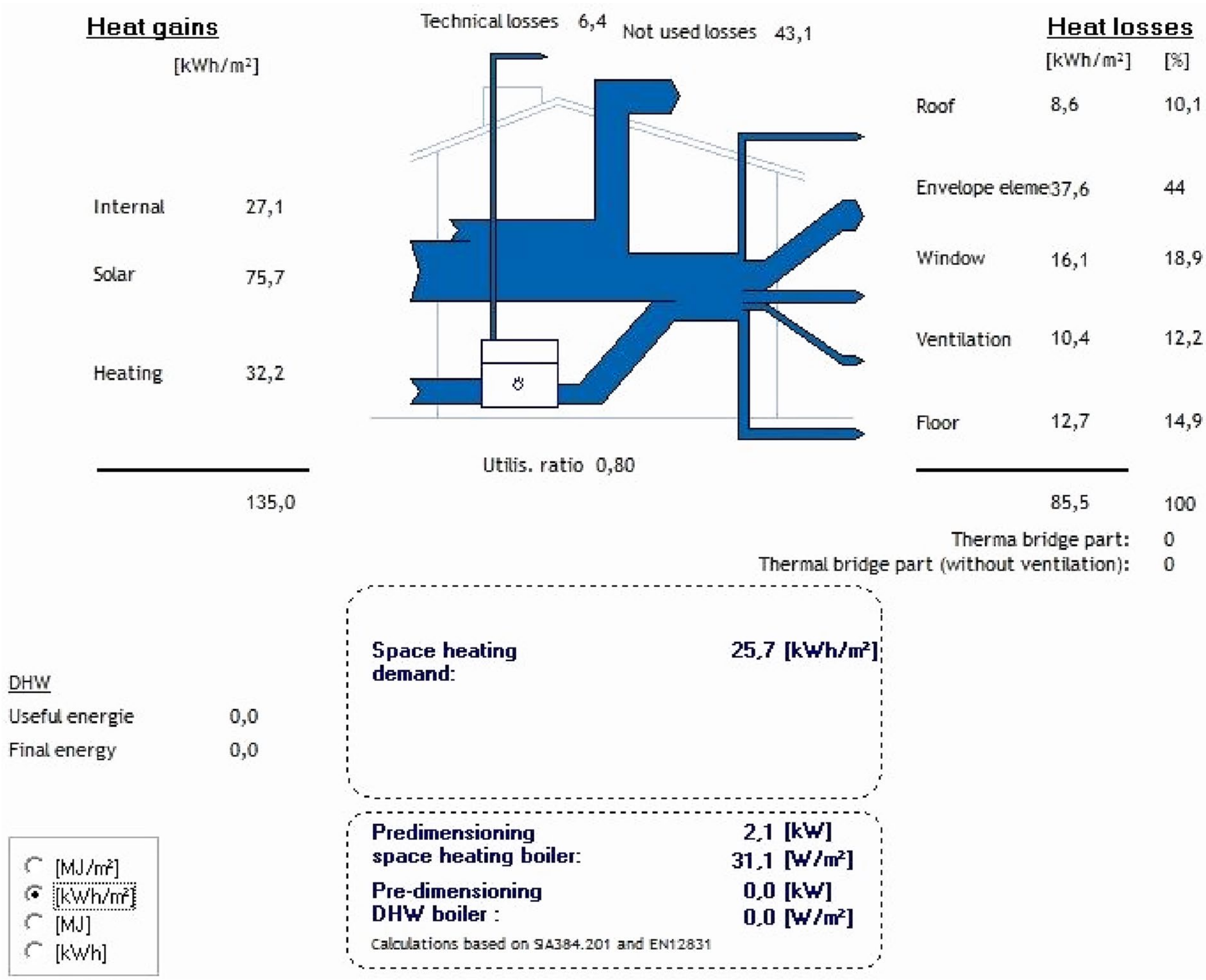


**Fig. 8** Sankey diagram for scenario 3 (4% OCF)

CED, and GWE) are compiled in Table 5. These values are obtained from the Lesosai software databases, studies or manufacturers. The objective is to show the main materials used in each scenario to know the environmental impact in the manufacturing process, transportation and raw materials. Indicators are shown per kg of product, to be able to compare the data (MJ/kg or kg $CO_2$eq/kg).

Regarding conventional materials, most of the data shown in Table 5 has been obtained from the Lessosai Software database (OSB board, bitumen sealing, steel, Swisspor PUR Premium, acrylpaint, gypsum plasterboard, rock wool, extruded polystyrene (XPS)). Except for aquapanel knauf, this is a lightweight cement board for outdoor use, whose data has been extracted and processed from the technical specifications of the product [66].

For the materials used in the different scenarios, the data has also been obtained from the manufacturers, such as hemp concrete and isotex. Bricks with mixtures of OCF and WS have been obtained from different studies.

Figure 12 shows the required energy and $CO_2$ eq differences for each material. The differences between conventional materials and biowaste-based materials can be observed in the graph.

The original building (scenario 0) was the one with the lowest energy consumption for heating, that is, of all the scenarios analysed it was the most efficient. However, when analysing the energy used to produce the materials and the $CO_2$ emission rates, it is observed that they have higher rates compared to biowaste-based materials. The energy required to manufacture conventional materials is non-renewable, except for the OSB panel that requires energy of 35.82 MJ/kg, with more than 60% of this energy being renewable.

Isotex is the biowaste-based material with the highest energy consumption and $CO_2$ emissions. The energy consumed for its manufacture amounts to 7.11 MJ/kg (of which 63% comes from renewable energy).

Hemp concrete requires very little energy to manufacture compared to other materials and exhibits negative carbon emission because during the growth of the hemp plant it

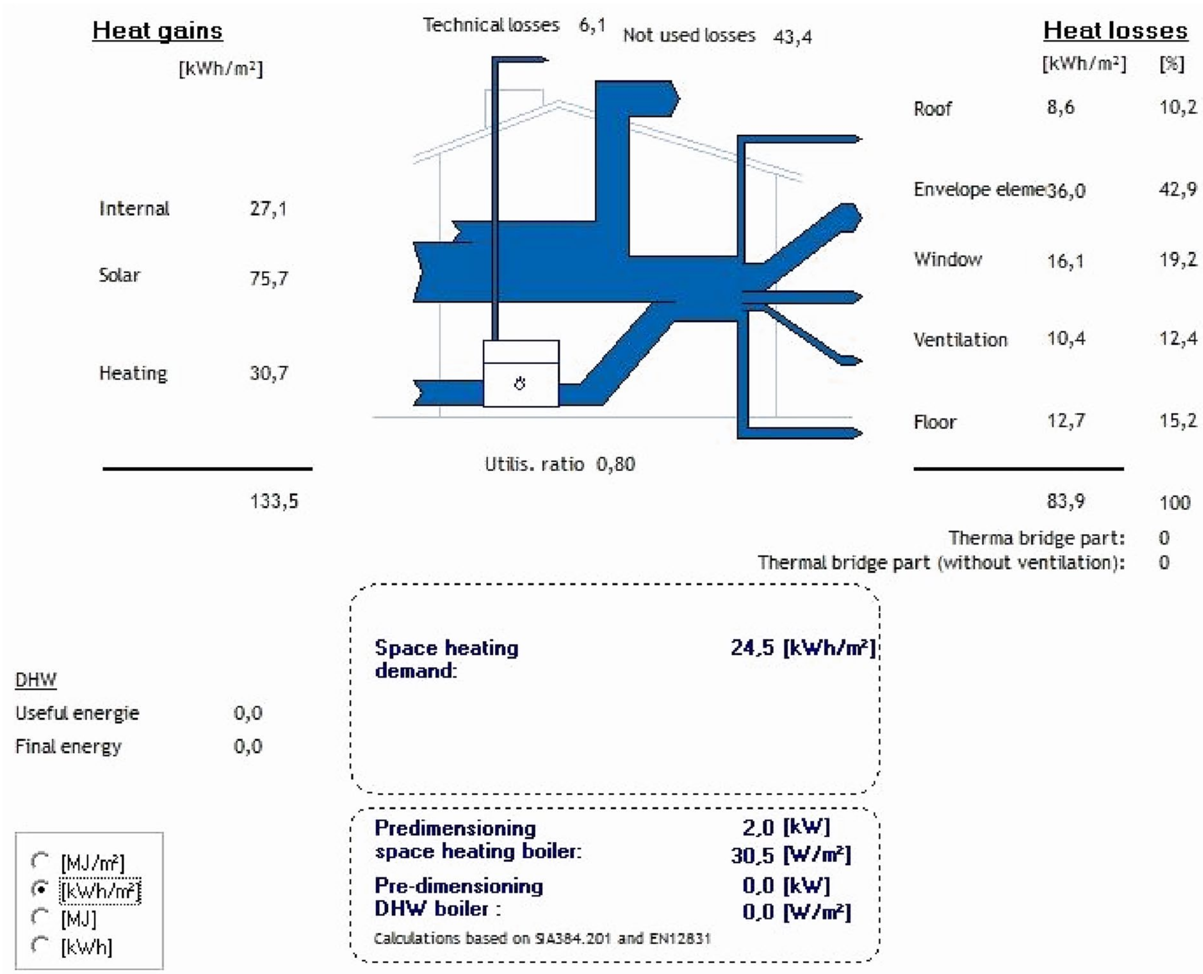


**Fig. 9** Sankey diagram for scenario 4 (8% OCF)

absorbs $CO_2$ from the atmosphere and even after its use as concrete it continues to absorb $CO_2$ from the atmosphere.

As for bricks with mixtures of OCF and WS, they require very little energy compared to other materials and emit an equally small amount of $CO_2$. Therefore, despite their worst thermal behaviour, they are the materials with the lowest energy consumption in their manufacturing stage.

## Discussion

Currently, there is a wide variety of waste-based materials from different waste that are viable for sustainable construction. Although a brief review of the reuse of waste as substitutes for raw materials in construction materials has been carried out, the great potential they have in the construction sector is highlighted.

Construction is the sector that generates the highest percentage of waste, representing 37% of the total waste generated in the European Union [4]. The reduction of waste in the sector can be focused on two ways: introducing waste in the production of construction materials, or else, reusing the waste generated in the sector.

After the bibliographic review, it is observed that the number of studies aimed at the reuse of waste in the production of construction materials has been increasing in recent years. This interest is caused by the policies of the European Union, so it is a fact that in the coming years there will be a strong introduction of waste-based material in the construction sector. Among the studies, it highlights the use of waste for the manufacture of thermal insulation, bricks, cement, mortar and concrete.

Among the main types of waste used for the manufacture of thermal insulation, agricultural waste stands out. Agricultural waste only represents 1% of the total waste generated [4], but due to its easy availability, it can be easily used and also at a low cost. Thermal conductivity of agricultural wastes is comparable to current conventional thermal insulation (mineral wool, polystyrene, or polyurethane) [19]. However, an increase in thickness can be necessary to achieve

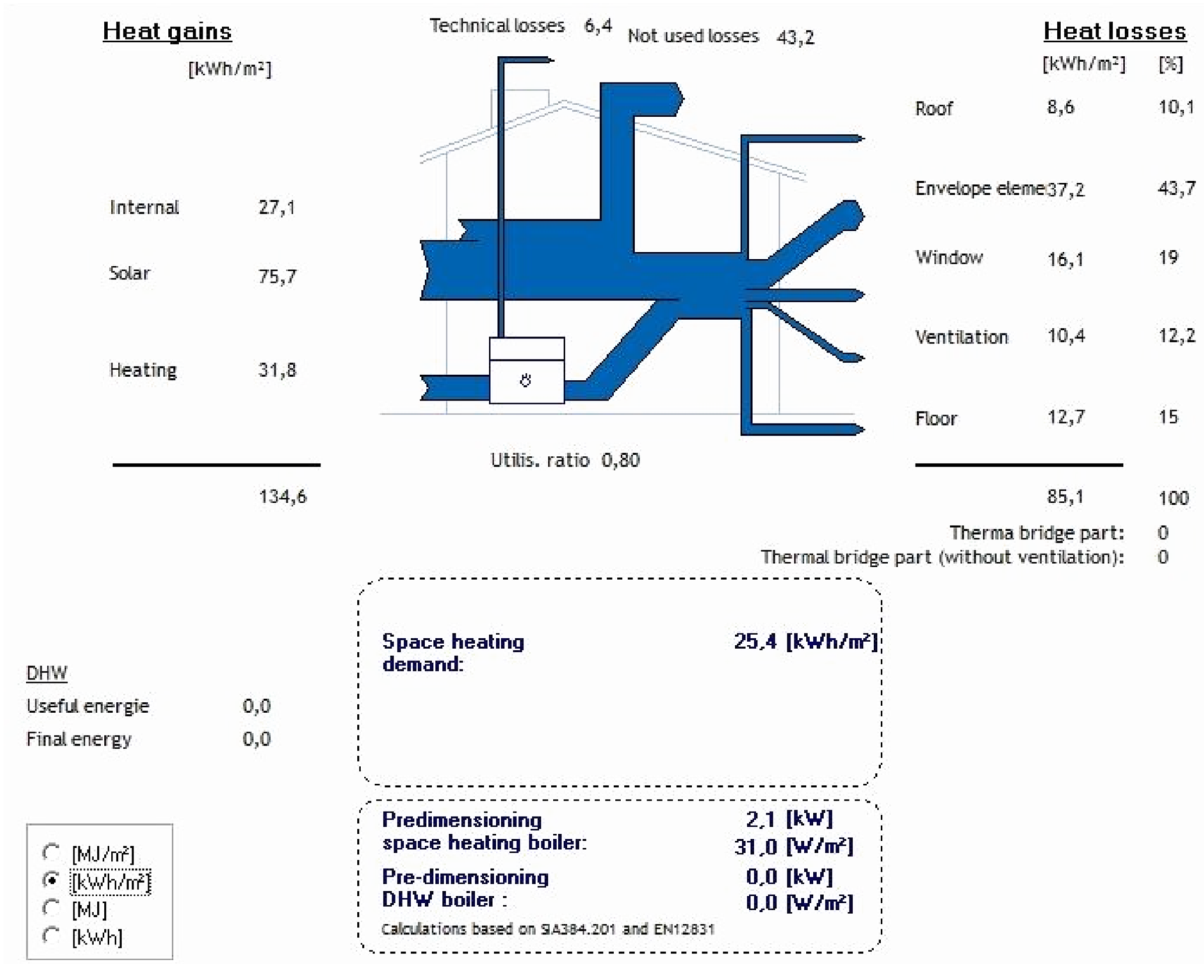


**Fig. 10** Sankey diagram for scenario 5 (3% WS)

thermal resistance similar to conventional insulation [23]. This type of waste can also be used in the structure of buildings in the production of bricks, providing them with greater thermal resistance.

Regarding the production of bricks, they can be produced with all the waste listed. In this case, the introduction of agricultural residues in ceramic brick mixtures, produce bricks with a lower thermal conductivity reducing the mechanical properties [25]. In general, the addition of residues in the production of bricks reduces the compressive strength, so the mixtures must be analysed. However, mixtures with marble or granite waste come to equal or exceed the mechanical properties of conventional brick [51]. Finally, the use of waste for the production of cement, mortar or concrete, causes an effect similar to the production of bricks. Adding certain residues causes variations in mechanical properties and durability concerning conventional materials, so the mixture must be controlled.

Therefore, waste-based materials can be used as a structure or as thermal insulation. However, as a structure, it is necessary to adapt the waste mixtures to meet quality standards and to be able to guarantee minimum resistance. The use of biowaste-based materials, from agricultural waste, allows improving the thermal resistance of materials such as bricks or concrete and thus improving the thermal envelope.

In this case, the thermal implications of biowaste-based materials in construction are analysed. The analyzed studies evaluate the thermal and mechanical properties of materials based on waste; however, no studies have been identified that apply the use of waste in the thermal envelope of buildings. Waste-based materials from agricultural waste are selected due to the ease of obtaining data on their thermal properties.

In the first place, the thermal behaviour of 20 cm of biowaste-based materials against a sinusoidal disturbance is analysed. Among the results obtained, hemp concrete and isotex stand out. Both materials allow obtaining very stable temperature with a decrement factor of 0.0655 and 0.0313. In addition, they generate a time lag greater than 9 h. The results obtained with both materials are due to the introduction of agricultural residues in their production, which

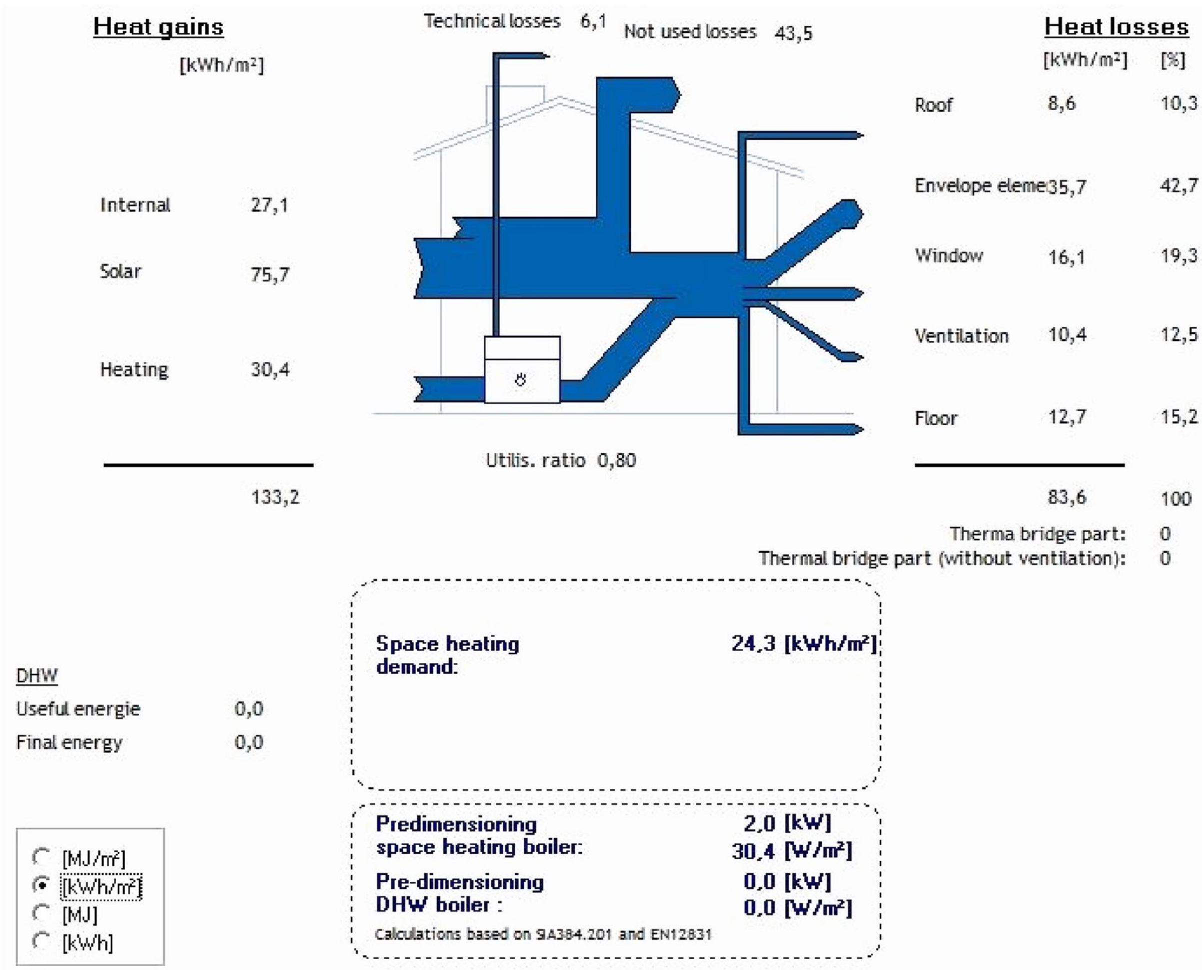


**Fig. 11** Sankey diagram for scenario 6 (7% WS)

allow obtaining very low thermal conductivities (0.071 and 0.104 W/(m·K)). In addition, the thermal capacity of the material helps to reduce the decrement factor and increase the time lag.

The use of bricks with mixtures of agricultural residues offer a worse response than hemp concrete and isotex. However, despite having a worse thermal behaviour, a smaller decrement factor and a greater time lag are observed compared to a conventional brick. For all bricks with agricultural residues, the decrement factor is reduced to 54% in the case of adding 7% WS. Regarding the time lag, it improves slightly increasing up to 8% for bricks with 7% WS.

If the four types of simulated bricks are compared, it is observed that when the bricks have a greater amount of agricultural residues, the wave generated on the surface is more stable. Increasing the amount of OCF and WS generates a reduction in thermal conductivity and density compared to brick without residues, this phenomenon is due to the decomposition of the residues in the clay body increasing the porosity of the material [25, 61]. However, the compressive strength is reduced as more residues are added. Thus, in the case of bricks with 4 and 8% OCF, the compressive strength is 31.5 and 24.8 MPa and in the case of bricks with 3 and 7% WS, the compressive strength is 26.6 and 18.1 MPa [61]. Therefore, taking into account the effect on both properties, OCF brick allows higher compressive strengths.

By introducing biowaste-based materials into the model building and analysing the annual energy consumption using the Lesosai software, the energy performance of the materials can be analysed. Different scenarios are analyzed, where the materials used in each wall are modified. The wall of the base case (scenario 0) has 1.5 cm granite, 1.25 cm of aquapanel knauf, 8 cm XPS and 4 cm rock wool, which means a total thickness of 14.75 cm, plus the inside layer with 2.6 cm of Gypsum plasterboard and 0.02 cm of Acrylpaint.

In scenario 1, the 14.75 cm are replaced by 15 cm of hemp concrete and 4 cm expanded cork panels growancor. By introducing this biowaste-based material, the heating demand of the building concerning scenario 0 increases 1.1 kWh/m$^2$, and the power of the boiler is by 0.1 kW. In

**Table 4** Summary of simulations performed with Lesosai software

| Scenario | Description | Space Heating Demand [kWh/m$^2$] | Power heating boiler [kW] | Heat Gains [kWh/m$^2$] | Heat Losses [kWh/m$^2$] |
|---|---|---|---|---|---|
| 0 | Base case | 10.7 | 1.4 | 116.2 | 64.0 |
| 1 | 15 cm of Hemp Concrete | 11.8 | 1.5 | 117.5 | 65.7 |
| 2 | 25 cm of Isotex | 10.9 | 1.4 | 116.4 | 64.3 |
| 3 | 15 cm of 4% OCF | 25.7 | 2.1 | 135.0 | 85.8 |
| 4 | 15 cm of 8% OCF | 24.5 | 2.0 | 133.5 | 83.9 |
| 5 | 15 cm of 3% WS | 25.4 | 2.1 | 134.6 | 85.1 |
| 6 | 15 cm of 7% WS | 24.3 | 2.0 | 133.2 | 83.6 |

**Table 5** Life cycle assessments of material materials

| Material | NRE [MJ/kg] | CED [MJ/Kg] | GWP [Kg $CO_2$eq/kg] |
|---|---|---|---|
| Aquapanel Knauf | 0.230 | 2.671 | 0.357 |
| Extruded Polystyrene (XPS) | 98.58 | 100.29 | 13.89 |
| Rock Wool, 100 kg/m$^3$ | 15.34 | 16.55 | 1.1 |
| Gypsum plasterboard | 5.87 | 6.23 | 0.364 |
| Acrylpaint | 15.19 | 15.69 | 1.362 |
| Swisspor PUR Premium | 101.91 | 104.34 | 7.18 |
| Steel | 27.8 | 28.9 | 1.83 |
| Bitumen sealing | 44.18 | 45.11 | 3.177 |
| OSB board | 13.42 | 35.82 | 0.64 |
| Hemp Concrete | 3.000 | 3.000 | − 0.268 |
| Isotex | 2.578 | 7.118 | 0.384 |
| Brick OCF 4% | 0.497 | 0.776 | 0.085 |
| Brick OCF 8% | 0.241 | 0.861 | 0.097 |
| Brick WS 3% | 0.589 | 0.785 | 0.083 |
| Brick WS 7% | 0.365 | 0.869 | 0.087 |

scenario 2, the 15 cm hemp concrete is replaced by a 25 cm isotex wood-cement block. In this case, the energy demand concerning scenario 0 increases by 0.2 kWh/m$^2$; maintaining the same power as the boiler. However, in both cases, a thicker wall is needed to maintain the indoor temperature, since they have 4 cm of expanded cork panels.

Finally, in scenarios 3, 4, 5 and 6, higher energy demand is obtained compared to the previous scenarios. These scenarios use 15 cm of brick and 4 cm of expanded cork panels. However, if these scenarios are compared, it is obtained that the scenarios with the lowest energy consumption are those with the highest percentage of agricultural residues. The most efficient scenario is the one that uses bricks with 7% WS. However, in these cases, it would be necessary to increase the thickness of the thermal insulation to maintain an energy demand similar to the base case scenario.

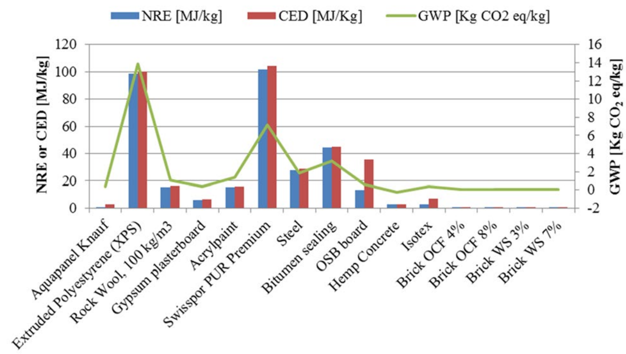


**Fig. 12** NRE, CED and GWP of materials

One of the advantages of using biowaste-based materials is the more stable indoor temperatures in buildings. After analysing the behaviour of all biowaste-based materials, the result obtained shows that all of them generate waves with a smaller decrement factor and a larger wave time lag (Fig. 4).

In addition to taking into account the energy consumption during the maintenance stage, the energy consumed in the manufacturing of the materials must be analysed. Thus, although scenario 0 is the most efficient, it uses materials with higher energy consumption in the manufacturing stage. Scenarios with hemp concrete and isotex (11.8 and 10.9 kWh/m$^2$) produce energy consumption similar to scenario 0 (10.7 kWh/m$^2$); however, the NRE and CED indicators show low values compared to conventional materials. In addition, these types of materials help to fix carbon from the atmosphere [58].

## Conclusions

Construction is the sector that generates the greatest amount of waste, so it is necessary to rethink civil construction to reduce waste and consumption of natural resources. In this study, a search has been carried out on the types of waste that can be introduced in the construction sector and it is analysed how it modifies the properties of conventional materials. In addition, the thermal properties of these new compounds were evaluated on the thermal comfort of the home and their environmental impact. The main conclusions are:

- Agricultural waste can be used as thermal insulation due to its low conductivity; however, it has worse thermal properties than conventional materials. They can also be part of the structure of the house in combination with bricks, improving the thermal properties.
- The introduction of residues in conventional materials (bricks, concrete, cement, mortars), in general, improves the thermal behaviour but can affect the mechanical properties.
- The biowaste-based analyzed materials generate a better thermal response than conventional materials. Hemp concrete and Isotex are the materials that cause a softer temperature (lower decrement factor) and cause a wave with a greater phase shift (greater time lag).
- When analysing bricks with mixtures of OCF and WS, mixtures with a higher percentage of residues cause a wave with a lower decrement factor and a longer time lag. However, the results are worse than those obtained for Isotex and Hemp Concrete.
- From the point of view of energy efficiency, the analysed scenario building built with conventional materials is the scenario with the best thermal performance (10.7 kWh/$m^2$). However, the main insulation used, XPS, generates a greater environmental impact of 13.89 kg $CO_2$/kg.
- Of the analysed biowaste-based materials, the isotex scenario presents similar results to the base case. The energy consumption of the scenario with isotex is 10.9 kWh/$m^2$ with a lower environmental impact than the base case with a value of 0.384 kg $CO_2$/kg.
- The biowaste-based materials with the lowest thermal performance are the OCF and WS bricks. Thermal performance improves as the amount of agricultural waste increases. The results obtained are far below the results obtained with isotex or hemp concrete. However, these bricks have a better thermal response than conventional bricks.
- Materials such as hemp concrete, in addition to being a sustainable material and offering thermal performance similar to conventional materials, allows the absorption of carbon from the atmosphere.

The use of waste as a complement to construction materials allows reducing the environmental impact of buildings not only during the maintenance of buildings (thermal comfort) but also allows the construction of more sustainable buildings. The commercialization of these materials and their use in new construction or renovations will help to achieve the European objectives of achieving economic net $CO_2$ emissions by the year 2050. The analyzed techniques allow a transition towards a regenerative economy, where ecosystems are not degraded and allow the economic growth of the sector.

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**Data availability** All data generated or analysed during this study is included in this published article.

## Declarations

**Conflict of 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.



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