Energy & Buildings 367 (2026) 117794

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Valorisation of wood fibre waste in gypsum composites for green building applications☆

Manfredi Saeli [a,*], Rosanna Leone [b], Giada La Scalia [b], Adriana Calà [a], Marinélia N. Capela [c], Tiziana Campisi [a]

[a] Department of Architecture, University of Palermo, Viale delle Scienze Bld. 8-14, 90128 Palermo, Italy
[b] Department of Engineering, University of Palermo, Viale delle Scienze, Bld. 8, 90128 Palermo, Italy
[c] Department of Materials and Ceramic Engineering, CICECO – Aveiro Institute of Materials, University of Aveiro, 3810-193 Aveiro, Portugal

ARTICLE INFO

Keywords:
Waste and by-product reuse
Biocomposite material
Sustainable construction materials
Circular economy
Energy simulation
Multicriteria assessment

ABSTRACT

The construction sector significantly contributes to environmental degradation due to its high consumption of non-renewable resources and carbon emissions. This study presents the development of a gypsum-wood waste biocomposite, as innovative and sustainable material for construction applications. The research investigates the incorporation of this abundant yet underutilized industrial by-product into a gypsum-based matrix, aiming to reduce environmental impact. The wood fibre waste was reused without pre-treatment, ensuring a simple and scalable production process. Experimental results indicate that increasing wood waste content progressively reduces thermal conductivity, from 0.35 W/mK to 0.24 W/mK, significantly improving insulation properties. Simultaneously, density decreases from 950 kg/m^3 to 720 kg/m^3, making the material lighter and easier to handle. However, a trade-off is observed in mechanical performance, as compressive strength decreases from 8.5 MPa to 3.0 MPa at the highest wood waste content of 10 wt%. Despite this, mixtures containing 2–4 wt% wood waste maintain mechanical strengths between 4.8 and 6.2 MPa, making them suitable for non-structural applications such as insulating panels and eco-friendly plasters. Additionally, preliminary virtual modelling and energy simulation were implemented to isolate the energy contribution of the produced mixes in a building model under Mediterranean-Continental climatic conditions (represented by the city of Rome). Also, a multicriteria analysis was implemented to rank the produced mixes and identify the optimal compromise between material's functional performance, environmental impact, and economic feasibility. Obtained results highlight that the optimal formulation balances insulation efficiency and mechanical properties while minimizing environmental and economic drawbacks. The direct reuse of untreated wood fibre waste enabled the development of lightweight gypsum bio-composites with improved insulation performance suitable for non-structural building applications. Finally, the best performing formulation was benchmarked against commercial product to investigate the possible positioning of the proposed biocomposite. This bio-composite represents a viable alternative to conventional materials, aligning with circular economy principles and European sustainability policies such as the Green Deal and Renovation Wave.

1. Introduction

The construction sector is one of the largest consumers of non-renewable resources and a major contributor to environmental degradation and global greenhouse gas emissions. In the European Union, buildings accounted for approximately 34% of energy-related CO_2 emissions and about 40% of total energy consumption [1]. Globally, the built environment is estimated to generate around 37% of total emissions, reaching up to 70% in urban areas [2].

Given that, a large portion of the existing building stock is expected to remain in use until at least 2050, its energy performance will continue to play a crucial role in determining the environmental sustainability of the sector in the coming decades [3]. Furthermore, rapid urbanization, especially in developing countries, is driving growing demand for new

☆ This article is part of a Special issue entitled: 'ENB_Ecological Buildings' published in Energy & Buildings.
* Corresponding author.
E-mail address: manfredi.saeli@unipa.it (M. Saeli).

https://doi.org/10.1016/j.enbuild.2026.117794
Received 6 February 2026; Received in revised form 19 May 2026; Accepted 8 June 2026
Available online 11 June 2026

buildings and infrastructure further intensifying the environmental impact of conventional construction materials and manufacturing processes [4]. At the same time, global waste generation is one of the most pressing environmental challenges, with municipal solid waste expected to grow to 3.8 billion tonnes by 2050, generating increasingly significant environmental and economic impacts [5]. In this context, industrial by-products and post-consumer residues continue to represent a critical source of environmental pressure, with millions of tonnes ending up in landfills or being incinerated every year [6]. Among these, wooden waste from the construction, furniture, and forestry industries represents a significant fraction [7]. According to recent studies, even under the most optimistic circular economy scenarios, only up to 50% of global wood waste is expected to be recycled by 2050, compared to roughly 30% in a business-as-usual scenario [8].

Recent FAO statistics further highlight the scale of the challenge: in 2023, the global production of wood-based panels reached approximately 381 million m^3, marking a 4% increase compared to 2019, while industrial roundwood removals amounted to 1925 million m^3 [9]. At the national level, Italy stands out as a leader in wood recycling, with the Rilegno Consortium reporting the recovery of 1.7 million tons of wooden packaging in 2022, corresponding to a recycling rate of 62.7%, and the regeneration of about 900,000 tons reintroduced into the market, equivalent to nearly 70 million pallets [10]. However, despite these recycling efforts, a substantial portion of wood waste remains underutilized, often ending up in landfills or being used for low-value applications [11].

In recent years, research has increasingly focused on innovative strategies to valorise wood fibre waste (WFW) within a circular economy framework, aiming to reduce environmental impact and promote sustainable solutions in the agricultural, industrial, and construction sectors [12]. Literature indicates that research efforts are mainly directed toward four key areas: i) use of wood residues to improve soil fertility, ii) development of innovative bio-composites, iii) energy recovery through thermochemical processes, and iv) incorporation of sustainable materials in construction.

Initial studies mainly investigated the potential of WFW in agricultural and bioeconomy applications, demonstrating its ability to improve soil quality and support circular biomass management systems [13,14]. Parallel research explored the conversion of wood residues into innovative bio-composites and engineered materials capable of partially replacing conventional raw materials [15]. At the same time, thermochemical processes, such as pyrolysis, were investigated as alternative strategies for energy recovery and biofuel production [16].

More recently, increasing attention has been directed toward the incorporation of wood-based residues into sustainable construction materials, driven by the need to reduce both waste disposal and the environmental footprint of buildings [17,18]. Previous studies demonstrated the feasibility of using wood-derived waste in alkali-activated materials, lightweight composites, and 3D-printable components for architectural applications [19–24]. These investigations highlighted important advantages in terms of lightweight performance, waste valorisation, and environmental sustainability.

Recent studies have also highlighted the growing interest in low-carbon gypsum, cementitious, and alkali-activated materials aimed at improving thermal efficiency, reducing embodied environmental impacts, and promoting the incorporation of secondary raw materials within building systems [25,26]. These investigations further confirm the strategic role of lightweight and waste-based composites in supporting the transition toward more sustainable and resource-efficient construction practices.

However, the current literature remains highly fragmented, as most studies focus either on cementitious systems, specific biomass fractions, or isolated material properties.

In particular, at the best of the authors knowledge, the combination of WFW with gypsum-based matrices remains largely unexplored. To date, only limited studies have investigated organic biomass incorporation in gypsum mortars [27,28], mainly focusing on hygrometric regulation and basic mechanical behaviour. Consequently, key aspects such as thermal insulation performance, integrated engineering behaviour, scalability, and building energy implications are still insufficiently addressed.

Given those premises, the novelty of this study consists in filling the gap by proposing an innovative bio-composite where gypsum serves as binder and WFW, deriving from industrial sawmill, acts as the primary aggregate without requiring pre-treatment. Hence, the primary objective of this study stands in the development of a novel and sustainable building material with potential for future industrial implementation, thereby reducing the reliance on virgin raw materials while valorising an abundant and clean waste resource. Furthermore, the research seeks to establish a viable alternative to conventional biomass waste disposal practices, such as the usual landfilling and incineration, offering clear environmental benefits and aligning with climate neutrality strategies [29]. Lastly, the principles of the Circular Economy and Industrial Symbiosis are here promoted, enabling the integration of waste streams into new value chains and enhancing resource efficiency across sectors. Unlike previous research, which has primarily investigated cellulosic waste as a filler or additive in cementitious composites [30], to the best of the authors' knowledge, this work explores the complete replacement of conventional aggregates within the investigated gypsum-based formulations, thereby enhancing resource efficiency and contributing to the transition toward more sustainable building practices.

In addition, this study implemented a multi-criteria decision making (MCDM) approach to evaluate the optimal formulation based on weight-driven decisional matrix assessed by experts of the construction field. This methodological framework allows a comprehensive material assessment by considering not only the physical and mechanical performance, as evaluated at laboratory scale, but also compute environmental and economic factors, ensuring the best balance between sustainability and practical applicability. MCDM approach was already applied in the field of building and construction materials unveiling its potentials in selecting the best compromise solution among various alternative [3,31,32].

The integration of secondary raw materials into this context supports the objectives of the European Green Deal [33], the Renovation Wave strategy [34], and the Sustainable Development Goals (SDGs) [35], fostering the adoption of more energy-efficient and circular construction materials. Also, the findings of this research could support the development of low-impact building solutions, contributing to a more sustainable and resilient construction industry.

Accordingly, this study investigates the development of highly innovative gypsum-based biocomposites incorporating untreated WFW derived from industrial sawmills. Comprehensive experimental analyses were carried out to determine the relevant chemical-physical characteristics of the used WFW and evaluate its incorporation on the physical, functional, performance, and thermal behaviour of the developed materials. In addition, MCDM approach was implemented as a viable tool to rank, and identify, the best solution (mix) considering functional, economic, and environmental variables. Finally virtual modelling and energy simulations were implemented to assess the performance of the selected formulations intended for lightweight non-structural building applications, from both energy and performance perspectives.

The remainder of this paper is structured as follows: Section 2 describes the raw materials and methodology used for the development of the gypsum-wood bio-composite, highlighting its potential within a circular economy framework; Section 3 presents the experimental results, with particular emphasis on thermal and mechanical performance; Section 4 presents the MCDM implementation for the selection of the best compromise solution; Section 5 discusses the sustainability implications of the material and its possible applications in the construction sector; Section 6 introduces the virtual modelling and energy simulations; finally, Section 7 presents the conclusions and suggests future developments, including a detailed life cycle assessment in subsequent studies.

2. Materials and methods

2.1. Used raw materials

In this study, new sustainable biocomposite materials were developed, by combining a traditional gypsum-based binder and WFW, derived from an industrialized sawmill that produces large building component, here reused as aggregate.

From a regulatory standpoint, the WFW used in this research is classified under the European Waste Catalogue (EWC) code 03 01 05, which refers to "sawdust, shavings, cuttings, wood, particle board and veneer other than those mentioned in 03 01 04". This code applies to wood waste generated from wood processing industries, such as sawmills, provided that the wood has not been treated with hazardous substances (e.g., preservatives, paints, or solvents). As such, this waste material is considered non-hazardous and, hence, is suitable for reuse in eco-friendly construction applications, in line with current EU waste management directive [36].

The following materials were used in the formulation of the mixtures:

- Wall gypsum: binder, supplied by the Sicilgesso S.p.A. plant in Calatafimi Segesta (Sicily), CE-certified according to European regulations. The product was selected for its excellent adhesive properties and wide commercial availability, it ensures easy scalability for large-scale applications.
- Wood fibre waste: aggregate, consisting of a mix of wood chips and saw dust from industrial processing and post-consumer materials, deriving from fir tree wood waste and collected from a local sawmill in Partinico (Sicily). To uphold the principles of circular economy and minimize production costs, these waste materials – being safe and non-poisoned - were used without any preliminary treatment, serving as aggregate within the gypsum matrix.
- Potable water: liquid, sourced from the municipal water aqueduct, used to mix the slurry, in compliance with UNI EN 1008: 2003, ensuring the required quality standards for material production.
- Release agent: CS Distak, a natural resin-based product supplied by Gattocel Italia, used to facilitate the removal of specimens from moulds and prevent the adhesion of the mortar to containment surfaces.

2.2. Product mix design

The mix design of the biocomposite mixtures was carried out in accordance with UNI EN 13279–2:2014 [37], which establishes the requirements for gypsum-based mortars. To determine the optimal amount of WFW that could be incorporated in the mix, an incremental approach was adopted, based on the progressive addition of aggregate (wt%) and the evaluation of the mixture's workability (flow table test, as discussed in section 3.2 Mortars characterisation). As an initial reference, a mixture with a Water-to-Binder (gypsum) ratio (W/B) of 0.5 was used, following the manufacturer Sicilgesso recommendations. From that baseline, incremental quantities (wt%) of WFW were introduced with a 2 wt% step to the binder quantity, up to the minimum threshold of workability (equal to 10 cm as for the standard flow table test). With a 0.5 W/B ratio, it resulted that up to 4 wt% of WFW could be incorporated, beyond which the mixture became excessively dry and difficult to handle. To increase the amount of waste incorporation, the W/B ratio was progressively increased to improve the workability of the mixture. With a W/B ratio of 0.6, the admissible maximum WFW content increased to 6 wt%; while with a further W/B ratio of 0.7 it reached 10 wt%. However, when the W/B ratio was further raised to 0.8, the slurry became overly fluid, compromising mixture stability and exceeding the recommended consistency range of 15–17 cm specified in the standard. Therefore, that stepwise procedure allowed to define the practical incorporation limits of WFW as a function of the W/B ratio, providing a realistic basis for assessing the industrial feasibility of the material and possible real applications in construction practice. In light of the aforementioned discussion, Table 1 presents the produced specimens, along with the calculated W/B, Binder/Aggregate (B/A).

As discussed in following sections, all the produced mixtures were tested and characterized to evaluate their suitability and applicability in construction, in compliance with the UNI EN 13279–2:2014 [37] and the technical standards.

2.3. Processing details

In this work, WFW was reused as received from the sawmill, without any pre-treatments such as cleaning and decontaminating. In fact, the received wood waste did not present any dangerous or poisoned substances which may affect its use or justify any type of pre-treatment. Moreover, the waste was furnished by the company in a dry state, hence it was not necessary a drying treatment in oven. Finally, any sieving was performed to select granulometric ranges with the aim of understanding its full potential in total reuse. The followed methodology simplified the overall production process, making the biocomposite material more scalable for industrial applications while ensuring a safe, reproducible, and straightforward mixing procedure. Moreover, the non-need for any pretreatment increases the sustainability of the WFW reuse avoiding wasting energy for worthless processes.

Mixtures were prepared following the standardized procedure outlined in the already cited UNI EN 13279–2:2014 [37], under room environmental conditions (23 ± 2 °C and 50% ± 5% RH). Accordingly, the slurry was first blended manually with a spatula for 1 min and then mixed mechanically with a programmable automatic mixer (Automix mod. 65-L0006/AM, Controls) for an additional 1 min at low speed, maintaining a constant speed throughout the mixing phase. Raw materials were introduced in a predetermined sequence: water was added first, followed by gypsum, and finally WFW. Once the mixing operation was completed, the fresh slurry was poured into standard metallic moulds (40 × 40 × 160 mm), whose surfaces had been previously pretreated with the release agent to facilitate specimens removal and, thus, prevent from being stick to the sides of the mould with possible consequence of material losses, which would compromise the standardized geometry of the testing specimens. After filling, the mixture was manually compacted by light vibrations to ensure uniform material distribution and minimize air void formation, which could otherwise compromise the mechanical properties of the specimens. To achieve a flat and homogeneous surface, the excess material was removed using a metallic spatula, levelling the mixture to the edge of the mould.

Since gypsum is an extremely fast-setting binder, the demoulding times were rapid and adjusted according to the W/B ratio. More particularly, for a W/B ratio of 0.5, the setting process was rapid enough

Table 1
Experimental plan of the biocomposite specimens' production.

Specimen n.	W/B Ratio	B/A [wt%]
1		0
2	0.5	2
3		4
4		0
5	0.6	2
6		4
7		6
8		0
9		2
10		4
11	0.7	6
12		8
13		10
14	0.8	0

to allow demoulding after ~15 min, in accordance with the manufacturer guidelines. For mixtures with W/B of 0.6, the higher water content slowed the setting time, requiring ~30 min setting before demoulding. With the W/B of 0.7, the setting time was extended to ~45 min to ensure sufficient consistency before specimen removal.

After demoulding, testing specimens were stored at room temperature (20 ± 2 °C, 65% RH) for seven days until testing. In fact, unlike the cementitious materials (e.g., cement, OPC, hydraulic lime, etc.), which require long setting and curing times (28 days, as ruled by relevant standards) to complete mortars hydration and crystallization, gypsum-based specimens were tested after seven days, in compliance with the standard setting time for gypsum mortars.

2.4. Materials characterisation

To assess the suitability of the gypsum-based biocomposite incorporating WFW as a sustainable construction material, physico-chemical analyses were conducted along with testing to evaluate the material engineering performance.

The crystalline structure of WFW was analysed by X-ray diffraction (XRD), using a Malvern PANalytical, X'Pert Pro3 diffractometer equipped with a fast RTMS detector (PIXcel 1D). Measurements were performed with Cu Kα radiation (45 kV and 40 mA) over a 2θ range of 10–80°, employing a virtual step size of 0.020° and a virtual time per step of 200 s at room temperature. Phase identification was performed using PANalytical X'Pert High Score Plus PRO3 software. The chemical composition of WFW was determined by X-ray fluorescence (XRF) using an Axios system (PANalytical), equipped with the Omnian module. The morphology and microstructure of the wood waste were investigated by optical (Leica, EZ4HD) and scanning electron microscopy (SEM, Hitachi SU-70). True density was measured by helium pycnometry (Antoon Paar, Ultrapyc 5000), while bulk density was obtained by geometrical evaluation.

To evaluate the workability of the fresh mixtures, a flow table test was performed in accordance with EN 1015–3:1999 [38], using an automatic flow table (Controls mod. 63-L0037/E). The bulk density of the produced samples was determined after 7 days of curing, through geometric measurements, with the average value calculated from three specimens per formulation. The mechanical properties were evaluated following the specifications of UNI EN 13279–2:2014 [37] using a universal testing machine (Controls Automax 5, equipped with a 250 kN load cell). Bending resistance (BR) was determined through a three-point bending test, applying the load at a rate of 0.50 MPa/s with a support span of 100 mm. Uniaxial compressive strength (UCS) was assessed under a loading rate of 0.75 MPa/s. The reported values represent the average of three tests conducted on separate specimens, ensuring the reproducibility of the results. Finally, thermal conductivity (λ) was measured using a HFM-CT 1000 heat flow meter, in compliance with UNI EN 12667:2002 [39]. To ensure measurement accuracy, the specimens were pre-dried at 60 °C for 24 h to eliminate possible residual moisture, given the highly hygroscopic nature of gypsum. Each formulation underwent three independent tests, providing reliable data on the material insulating properties.

3. Results and discussion

3.1. Waste characterisation

The bulk density of the investigated fir WFW was determined in 90 kg/m^3, whereas its true density was measured at 1618.10 kg/m^3. The substantial disparity between these two values is indicative of the exceptionally high porosity of the material, which stems from its derivation from natural wood. Owing to its origin, WFW retains the intrinsic microstructural characteristics of lignocellulosic biomass, notably its highly porous and fibrous network [40]. The bulk density, which accounts for both the solid matrix and the voids between fibres and particles, is markedly reduced by the extensive presence of empty spaces in the aggregated residue. Conversely, the true density, which exclusively reflects the compact solid fraction of the material, aligns closely with the density range typically reported for hardwood species (1500–1650 kg/m^3) [41]. This contrast emphasizes that the lightweight character of WFW is not a result of chemical degradation or compositional loss, but rather of its preserved porous morphology. From an application perspective, this pronounced density gap is highly relevant. The low bulk density translates into reduced material density, making WFW particularly advantageous for the development of lightweight construction materials. Moreover, the high porosity enhances thermal and acoustic insulation performance, since air entrapment within the voids reduces heat transfer and dampens sound propagation [42]. Nevertheless, the same characteristics that provide functional advantages may also present limitations. High porosity can increase susceptibility to moisture absorption, dimensional instability, and biological degradation, which may compromise durability under real environmental conditions [43]. Lignocellulosic biomass is a heterogeneous material composed primarily of organic constituents, including cellulose, hemicellulose, and lignin, along with various inorganic components of diverse origins. The composition of natural biomass is influenced by several factors, such as plant species, plant part, age, growth conditions, geographic origin, and harvesting practices. [44] Consistent with these observations, the XRD pattern of the WFW, shown in Fig. 1, reveals a predominantly amorphous character [45], with only low-intensity diffraction peaks corresponding to cellulose polymorphs, specifically Cellulose Iα (JCPDS 00–056-1719) and Cellulose Iβ (JCPDS 00–056-1718).

The inorganic chemical composition of the WFW, determined by XRF, is dominated by CaO (46.88 wt%), followed by K_2O (10.08 wt%), P_2O_5 (9.50 wt%), and SiO_2 (7.21 wt%). Other significant oxides include SO_3 (6.50 wt%), MnO (4.54 wt%), TiO_2 (4.29 wt%), and Fe_2O_3 (3.65 wt %), while Al_2O_3, NiO, PdO, Cl, CuO, MgO, Na_2O, and ZnO are present in minor amounts (<3 wt%). The identified compounds are consistent with those reported in the literature [44], although it should be noted that the published results were obtained from high-temperature ash analyses, whereas - in this study - XRF was performed directly on the as-received biomass. A summary of the chemical composition of the wood waste is reported in Table 2.

Optical images (Fig. 2A–B) and SEM micrographs (Fig. 2C–D) provide clear evidence of the fibrous morphology of the wood residue, corroborating the outcomes of previous analyses. At higher magnification, the SEM observations highlighted a complex and irregular microstructural network composed of folds, ridges, and grooves, which are characteristic of lignocellulosic materials derived from natural wood [46]. This intricate architecture generates a markedly porous structure, a feature that significantly influences both the physical and functional

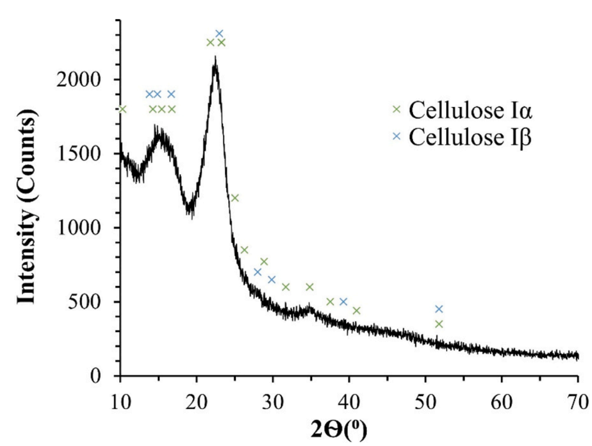

Fig. 1. XRD pattern of WFW.

Table 2
WFW chemical composition, as estimated by XRF.

Compounds	[wt%]	Compounds	[wt%]
CaO	46.884	Al_2O_3	2.530
K_2O	10.084	NiO	1.098
P_2O_5	9.498	PdO	0.795
SiO_2	7.208	Cl	0.758
SO_3	6.500	CuO	0.753
MnO	4.539	MgO	0.662
TiO_2	4.290	Na_2O	0.428
Fe_2O_3	3.654	ZnO	0.321

properties of the material intended for further applications in construction. From a structural standpoint, the high porosity contributes to the reduced bulk density of the residue, thereby enhancing its potential as a lightweight aggregate in biocomposite systems. In line with observations reported for other lignocellulosic fibres this morphological feature tends to improve thermal and acoustic insulation performance through the entrapment of air within the voids [47]. Additionally, the pronounced surface roughness and the presence of micro- and mesopores increase the specific surface area available for interactions at the material interface. That enlarged contact area resulted particularly advantageous as it can promote improved mechanical interlocking and enhance fibre–matrix adhesion, thereby contributing to superior mechanical integrity of the resulting composites [48]. Beyond structural reinforcement, however, it should be noted that the irregular and highly porous structure could also present challenges, such as moisture sensitivity and reduced durability under fluctuating humidity conditions, which may necessitate additional treatments or surface modifications to ensure long-term stability in specific applications, also considering the high hygroscopicity nature of the binder.

3.2. Mortars characterisation

The operating performance of the developed waste-based biocomposites is strongly influenced by the mixture composition, the quality of the raw materials, and the adopted production process. These factors directly affect key properties such as workability, density, and mechanical strength, ultimately determining the material suitability for sustainable construction applications.

As discussed, the high porosity of the WFW played a crucial role in shaping the physical characteristics of the developed mortars, making it essential to carefully balance the waste content and the water amount to maintain adequate workability. An improper dosage could compromise the setting and durability of the resulting slurry, whereas a well-optimized formulation ensures a homogeneous mixture, with a uniform distribution of aggregates and an appropriate balance between lightness, mechanical strength, and other performances such as the thermal conductivity.

Following, the influence of WFW content on material performances is analysed. In particular, the workability is shown in Figs. 3 and 4; the bulk density is presented in Fig. 5; the analysis of the mechanical characteristics is shown in Fig. 6A-B, BR and UCS respectively, while the thermal conductivity is presented in Fig. 7.

Figs. 3 and 4 illustrates WFW influence on the workability of the fresh slurry, evaluated from a comparison of the spreads on the flow table. It is observed that the initial spread values, determined for the virgin gypsum pastes (waste content equal to 0 wt%, cf. Table 1), increase following the water amount. More particularly, for virgin specimens n. 1 (W/B: 0.5), n. 4 (W/B: 0.6), and n. 8 (W/B: 0.7) spreads resulted 16, 23, and 27 cm, respectively. As previously said, the ultimate ratio 0.8 determined a too fluid slurry, hence, experimentation was not continued. The 0.7 formulation exhibited a quite high fluid nature, which hindered its suitability for practical shaping. Nonetheless, its elevated W/S ratio facilitated the incorporation of a greater fraction of

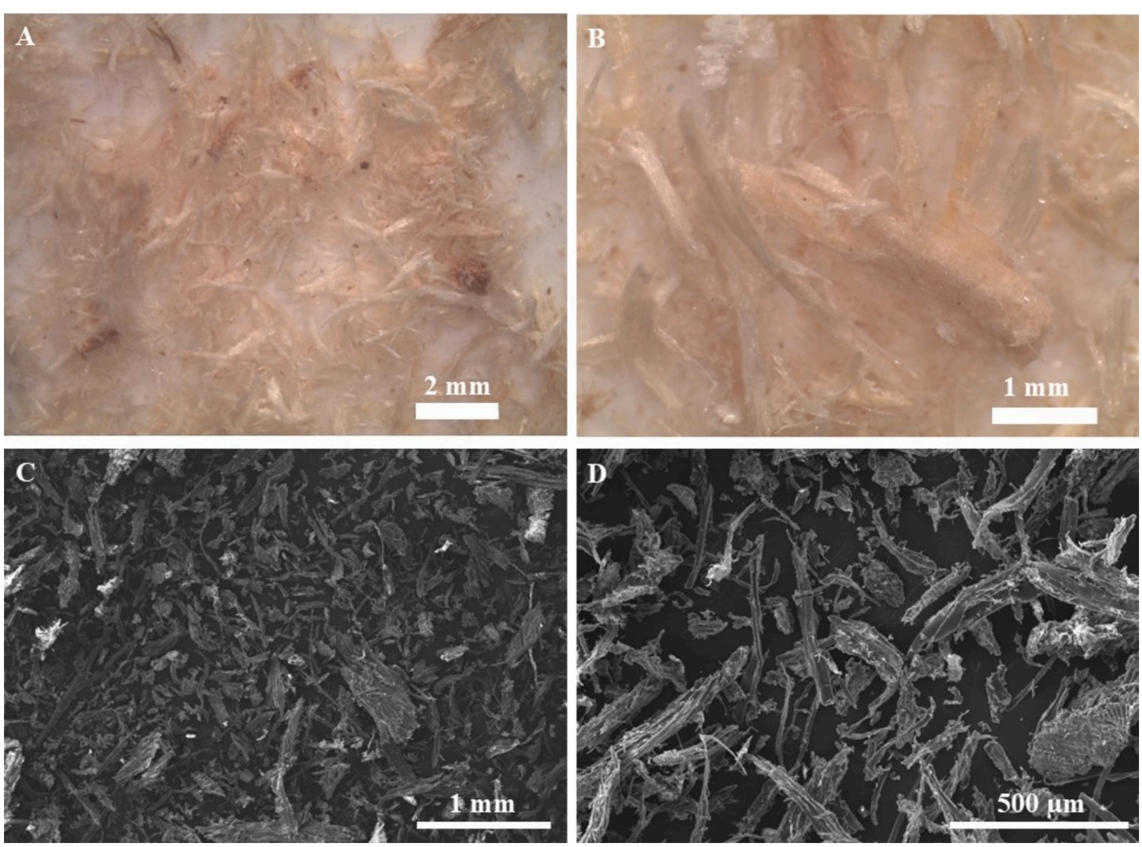

Fig. 2. WFW morphology and microstructure: (A, B) optical microscopy images; (C, D) SEM micrographs.

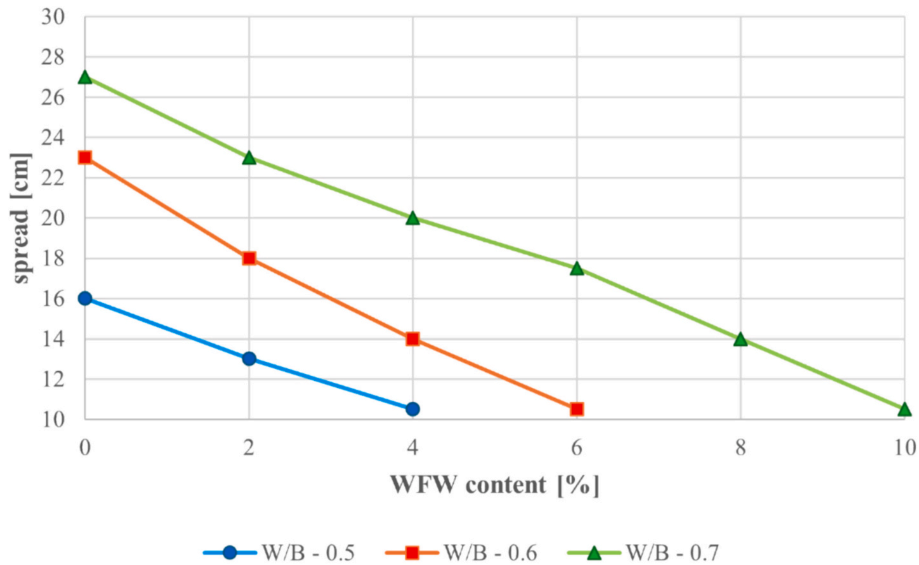

Fig. 3. Determined workability of the produced mixes: measured spread.

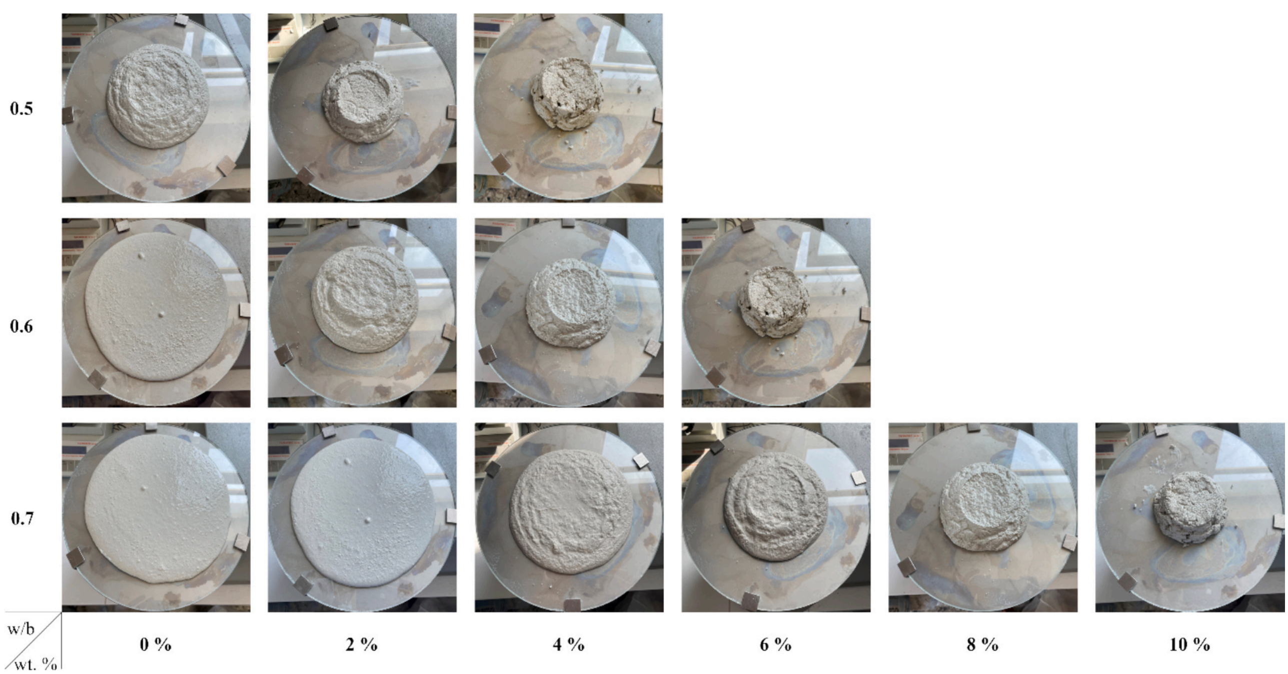

Fig. 4. Photographs of the spread slurries on the flow table (plate diameter: 30 cm).

WFW into the mixture, main scope of this study. As a general statement, it was also observed - across all formulations - a progressive reduction in flow spread with increasing WFW content. That reduction in workability can be ascribed to the pronounced water absorption capacity of the lignocellulosic waste, which diminishes the amount of free water available in the slurry to ensure adequate particle lubrication within the mixture. As a result, the slurry exhibited a more cohesive and pasty consistency, thereby limiting its flowability and reducing the measured spread on the flow table.

This observed trend is consistent with the findings of [28] that investigated the rheological behaviour of gypsum-based formulations incorporating lignocellulosic waste and reported similar reductions in workability with increasing biomass content. Ensuring a correct balance between water, binder, and aggregate ratios is therefore essential to prevent excessive loss of flowability while maintaining sufficient mixability for practical applications.

Fig. 5 shows the correlation between the wood waste content and bulk density in the cured material. Results indicate that the incorporation of WFW significantly influences the density of the mixtures, with variations depending on the W/B ratio. Moreover, as expected, an overall decrease is observed with increasing the waste content. In general, density decreases with increasing WFW quantity across all mixtures, which can be attributed to the lower bulk density of the waste particles compared to the considered binder material. At a W/B ratio of 0.5, the mixtures exhibit the highest density values, resulting equal to 1121 ± 2.23 kg/m^3, with a progressive reduction as the WFW content increases, up to 1074 ± 8.23 kg/m^3 for the 4 wt% waste incorporation. This trend suggests that in denser mixes, the addition of light WFW to the paste has a more pronounced effect. This trend is explained by the intrinsic porosity and lower density of wood compared to gypsum,

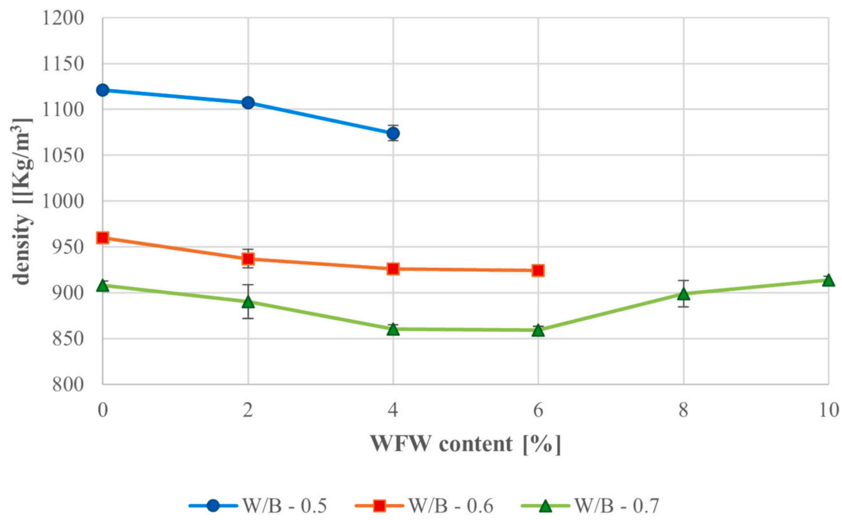

Fig. 5. Bulk density of the produced mixes.

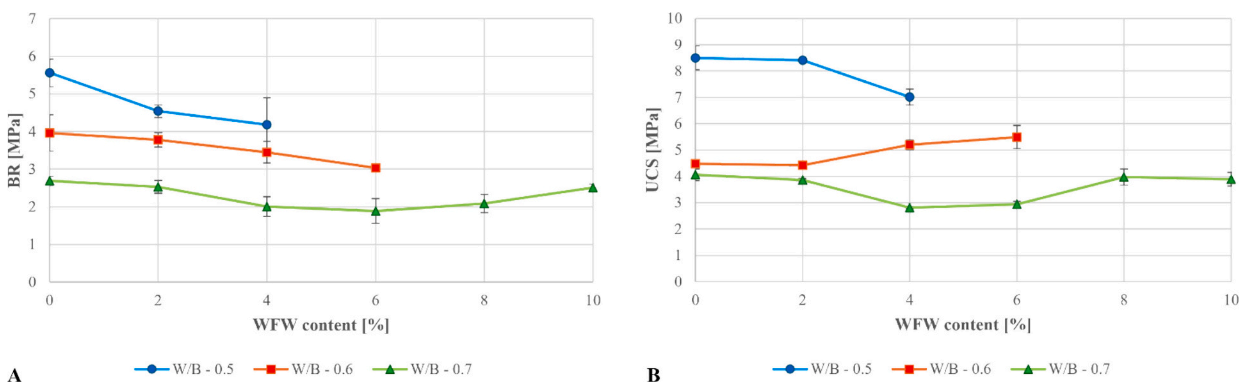

Fig. 6. Mechanical performance of the developed mixes: bending resistance (A), and uniaxial compressive strength (B).

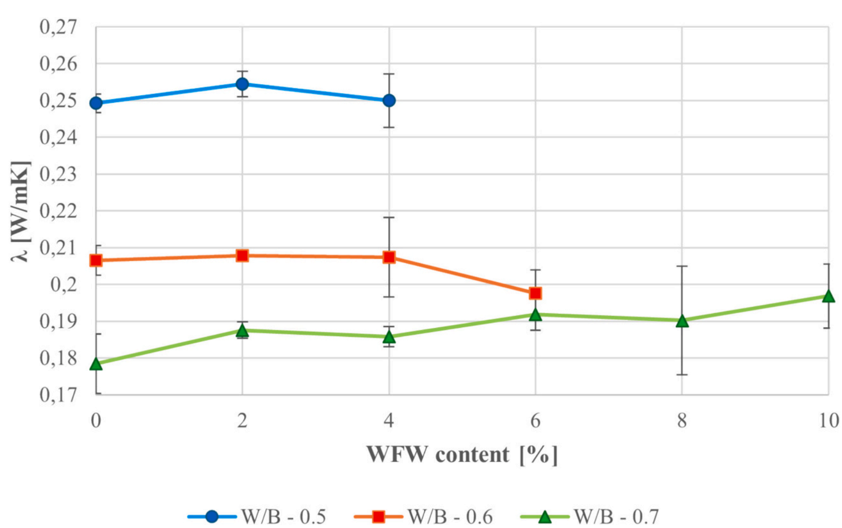

Fig. 7. Thermal conductivity (λ) of the produced mixes.

which leads to an overall reduction in the final mass of the composite. Similar effects have been reported in previous studies, such as [3,27,49] where the incorporation of lignocellulosic aggregates in biocomposite materials resulted in an increased porosity and a reduced bulk density. This characteristic makes the developed gypsum–wood biocomposite particularly suitable for lightweight applications, such as non-load-bearing elements, improving handling, ease of application, and reducing structural loads in construction. For mixtures with a W/B ratio of 0.6, the density values resulted lower (= 960 ± 6.15 kg/m^3) with a reduction steeper up to 4 wt% WFW (= 926 ± 3.54 kg/m^3), after which the trend almost stabilizes, indicating that beyond a certain limit, additional waste content does not further compromise compactness. At the highest W/B ratio of 0.7, density values are the lowest (= 908 ± 4.52 kg/m^3), reflecting the higher porosity of the material due to the highest amount of water. Subsequently, mixes exhibit a reduction steeper up to 4–6 wt% WFW (∼ 860 kg/m^3) and, interestingly, a recovery in density is observed at higher WFW contents (8–10 wt%) up to 914 ± 3.48 kg/m^3, which may be attributed to a filler effect, whereby fine waste particles occupy voids between coarser constituents, partially mitigating the porosity increase. Overall, the findings highlighted that both the W/B ratio and the proportion of WFW play a critical role in determining mixture density, with lower W/B ratios ensuring higher absolute values but showing greater sensitivity to waste incorporation.

The mechanical performance of the gypsum–wood composites is presented in Fig. 6A-B, where bending resistance (BR) and uniaxial compressive strength (UCS) are plotted, respectively, as a function of the WFW content for the three considered W/B ratios. In general, the incorporation of WFW leads to a reduction in both BR and UCS, although the extent of this effect is strongly dependent on the W/B ratio, as increasing the water content the mechanical performance tends to drop down. In fact, as well acknowledged, BR and UCS are strongly influenced by the W/B ratio, since increasing water content leads to higher porosity within the hardened gypsum matrix. Excess water, once evaporated during curing, leaves behind voids that weaken the microstructure and reduce the effective load-bearing section. This loss of compactness translates into lower mechanical resistance, as cracks can initiate and propagate more easily through the porous network. Consequently, mixtures prepared with higher W/B ratios systematically exhibit reduced strength compared to denser mixtures, where the binder matrix is more continuous and better able to transfer stresses.

For the considered specimens, the BR of the reference mixtures (0 wt % WFW) shows decreasing values with increasing W/B, ranging from 5.56 ± 0.37 MPa at W/B = 0.5 to 2.69 ± 0.12 MPa at W/B = 0.7. The addition of wood fibres resulted in a progressive reduction in BR for the mixtures with W/B = 0.5 and 0.6, reaching about 4.18 ± 0.72 MPa and 3.03 ± 0.01 MPa, respectively, at the highest WFW levels. This behaviour can be explained by the low stiffness of the fibres compared to gypsum along with a gap of adhesion of the gypsum molecules during curing, which reduce the matrix ability to resist tensile stresses in bending. These findings are consistent with [27] that reported a reduction in mechanical performance following the incorporation of organic waste into gypsum-based matrices for the lower cohesion of the composite structure. Conversely, the mixtures with W/B = 0.7 display a reduction in BR up to 4–6 wt% WFW (lowest value equal to 1.89 ± 0.33 MPa), followed by a partial recovery at 10 wt% (2.51 ± 0.09 MPa). This suggests that, at high water content, the finer fractions of the waste may improve the microstructural compactness by filling voids and making the matrix more compact and resistant, thereby mitigating strength loss. A similar phenomenon was noted by [27,30], where it was demonstrated that certain biomass-derived aggregates can improve matrix integrity at specific dosages due to their ability to create a more interlocked structure.

For the UCS, it is observed that it initially exhibits a quite stable strength up to 2 wt% WFW for all the *W*/W ratios. At W/B = 0.5, UCS values decrease steadily from 8.50 ± 0.45 MPa for the reference mix to around 7.01 ± 0.30 MPa at 4 wt% WFW. In contrast, for the mixtures with W/B = 0.6, it is followed by a modest increase reaching, from the initial value of 4.48 ± 0.12 MPa, 5.49 ± 0.44 MPa for the 6 wt% WFW formulation, indicating a possible reinforcing effect of the fibres within the matrix. At the highest W/B ratio (0.7), UCS goes considerably lower from 4.06 ± 0.22 MPa to 2.81 ± 0.04 MPa and is strongly affected by the fibres addition, although a recovery is again observed beyond 8 wt% WFW up to 3.98 ± 0.30 MPa. That behaviour highlights the dual role of wood fibres: while they reduce the load-bearing capacity of the gypsum matrix due to their lower intrinsic strength, they can also contribute to improved stress redistribution and crack-bridging mechanisms when present in sufficient amounts.

A comparison of the density results with the mechanical properties highlights a clear correlation between material compactness and strength performance. Mixtures with lower W/B ratios exhibited higher densities, which were consistently associated with superior bending and compressive strengths. As the WFW content increased, the density tends to decrease due to the lower specific density of the WFW itself and the increase in porosity caused by the addition of water content. Therefore, this reduction was mirrored by a loss in both BR and UCS. Conversely, at the highest 0.7 W/B ratio, the density values were the lowest and the mechanical properties the weakest, although both density and strength displayed a partial recovery at highest waste contents (8–10 wt%), suggesting a filler effect that reduced voids and improved matrix packing. These findings confirmed that density is a key indicator of the structural integrity of gypsum–wood fibre composites, with reductions in compactness generally leading to compromised mechanical performance.

Fig. 7 shows the thermal conductivity (λ) of the developed materials. The considered biocomposite mortars exhibit thermal behaviours strongly influenced by both the W/B and the amount of incorporated WFW. Generally speaking, increasing both the water and the WFW contents a lower λ was measured. Moreover, λ ranges between 0.178 ± 0.008 (specimen n. 8) and 0.254 ± 0.003 W/mK (specimen n. 2), which is consistent with lightweight gypsum-based materials. At a W/B ratio of 0.5, the mixes exhibit the highest λ values. The incorporation of WFW produces only minor fluctuations in this case, indicating that the dense and compact matrix largely governs heat transfer, and the addition of the lightweight WFW did not significantly affect the thermal conductivity. For the mixtures prepared with a W/B ratio of 0.6, slightly lower λ values are observed, in the order of 0.206–0.208 W/mK. This behaviour remains nearly constant up to 4 wt% WFW, after which a gradual decrease occurs down to 0.198 ± 0.006 W/mK. That implies that, at intermediate water contents, WFW incorporation begins to reduce solid-phase heat conduction. By contrast, the mixtures with the highest 0.7 W/B ratio show the lowest conductivity values of 0.178 ± 0.008 W/mK and 0.197 ± 0.009 W/mK. In this case, a slight increase in conductivity is observed with rising WFW content, which may be attributed to a competing effect: while the wood fibres are less conductive than gypsum, their addition at higher quantities tend to improve particle packing, as already observed for UCS, and reduce macro-voids with a filler effect, thereby offsetting the insulating effect of the improved porosity due to water. These findings are consistent with existing literature confirming that biomass incorporation lowers heat transfer in gypsum composites [27,49].

When compared these results to bulk density, it is evident that mixes with higher density, such as those developed with a W/B ratio of 0.5, show higher thermal conductivity, reflecting the dominant contribution of the continuous gypsum matrix to heat transfer. Conversely, mixtures with lower density, particularly clear at W/B = 0.7, achieve the lowest conductivity values, confirming the combined influence of increased porosity due to the water implementation and the intrinsically insulating nature of the WFW in restraining heat flow. The biocomposites with intermediate density (W/B = 0.6) display thermal conductivity values that fall between the two extremes, but with a more distinct sensitivity to WFW content, highlighting the complex interaction between reduced density and evolving the microstructure in controlling heat transport.

4. Selection of the best formulation by means of multicriteria approaches

The selection of the optimal formulation (i.e., alternatives) requires the simultaneous consideration of multiple, often conflicting, criteria. As showed in the previous sections, critical factors such as thermal and mechanical properties and physical performance must be carefully evaluated and balanced. Moreover, the sustainability in terms of the percentage of used WFW must be considered. Incorporating WFW in the biocomposite production process helps mitigate the environmental impact associated with the waste disposal. Moreover, higher percentage of WFW usage leads to reduced costs, as it lowers the gypsum incorporation. These two factors are directly interconnected with the volume of waste used, and therefore, this singular indicator will be employed to assess them.

Table 3 reports a synthesis of the score obtained for each formulation regarding each criterion.

To ensure a robust and meaningful ranking of the available options, it is first necessary to determine the relative importance of each criterion. In this study, two MCDM methods were employed: the Analytic Hierarchy Process (AHP) [50,51] was used to derive the weights of the criteria, while the VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [52], method was applied to obtain the final ranking of the alternatives.

The AHP, originally formulated by Saaty in the 1970s, is a widely adopted method within the field of MCDM, applicable to a broad range of complex decision scenarios [53]. AHP structures decision problems into a hierarchical framework, enabling Decision-Makers (DMs) to systematically analyse and prioritize various elements. The decision issue is decomposed into multiple layers, including the overall goal, relevant criteria, sub-criteria, and potential alternatives. This layered structure improves transparency and allows decision-makers to address each component individually. Elements at one level depend on those above them but are independent from others within the same level. Fig. 8 shows the hierarchical tree for the considered research study:

By integrating both subjective judgments and objective data, the method promotes a balanced and rational evaluation process through a compensatory model. To assess the relative importance of two elements at the same hierarchical level, in relation to a criterion from the level above, decision-makers conduct pairwise comparisons. The pairwise comparisons were provided by an expert in architectural engineering and sustainability issues in construction. The expert evaluated the relative importance of each criterion using Saaty's fundamental scale (1–9) [54], taking into account the specific objectives of this study. In particular, greater importance was attributed to thermal conductivity, bulk density, and sustainability, as these parameters directly influence the energy performance and environmental impact of the developed biocomposite materials. Conversely, mechanical properties were assigned lower weights, as the material is intended for non-structural applications. Each pairwise comparison judgment (Table 4) represents the element a_{ij} of the reciprocal pairwise comparison matrix, where $a_{ij} = 1/a_{ji}$, $a_{ii} = 1$ and n is the number of elements at a given level. Based on this matrix the weights qi for all n elements are derived using established techniques, such as the geometric mean approach, as documented in the literature [55].

Despite its structured nature, the AHP method is inherently influenced by the subjectivity of DMs, making inconsistency a frequent challenge [56]. Various factors can lead to inconsistent judgments, such as limited or imprecise information, uncertainty, cognitive distractions, human error, lack of domain knowledge, and the dimensionality of the comparison matrices [57]. As a result, evaluating the consistency of input judgments becomes a critical step in the AHP process. Over the years, numerous indices have been developed to quantify inconsistency in pairwise comparisons [50,58–61]. Among these, Saaty's Consistency Ratio (CR), proposed in 1980, remains one of the most adopted measures. It is calculated as follows:

$$CR = \frac{CI}{RI} \tag{1}$$

where the consistency index CI is given by:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

The Consistency Index (CI) depends on the maximum eigenvalue ($\lambda_{\max}$) of the pairwise comparison matrix. When judgments are fully consistent, the CI value is zero. To contextualize this measure, the Random Index (RI) is used, it represents the consistency index for a given n. If the CR exceeds a certain threshold, the matrix is considered inconsistent and should be revised. According to Saaty, a CR below 0.1 indicates a high level of consistency, while values up to 0.2 may still be acceptable under certain conditions [62]. However, if the CR surpasses 0.2, decision-makers are advised to re-evaluate their judgments to improve coherence. In this work the eigenvalue is 6.049 and the CR was equal to 0.8%.

After determining the weights associated with each criterion, the VIKOR technique is employed to rank the available alternatives. This method requires two main inputs: the set of criterion weights (wi, for $i = 1, \ldots, n$) and the performance ratings of each alternative (P_k, for $k = 1, \ldots, m$) with respect to each criterion. These performance scores, denoted as g_{ik}, form the elements of the decision matrix, where each row represents an alternative and each column corresponds to a criterion. The use of the VIKOR approach is particularly advantageous due to its low computational complexity, ease of implementation, and capacity to generate reliable and interpretable rankings. Furthermore, through proper calibration of its key decision parameter, VIKOR can account for multiple decision-making objectives, such as maximizing overall group satisfaction, minimizing individual dissatisfaction and promoting consensus, thus making it well-suited for complex, multi-perspective evaluation scenarios (Opricovic and Tzeng, 2004). The procedural steps of the VIKOR method are outlined below:

(a) For each criterion, determine the best (g_i^*) and worst (g_i^-) solutions:

$$g_i^* = \left\{ \left(\max_{\forall k} g_{ki} | i \in C' \right), \left(\min_{\forall i} g_{ki} | i \in C'' \right) \right\} \quad \forall i \tag{3}$$

$$g_i^- = \left\{ \left(\min_{\forall i} g_{ki} | i \in C' \right), \left(\max_{\forall i} g_{ki} | i \in C'' \right) \right\} \quad \forall i \tag{4}$$

Table 3
Decision matrix.

ID	W/B	WFW [wt%]	Workability [cm]	Bulk Density [Kg/m³]	Flexural Strenght [MPa]	Compressive Strenght [MPa]	Thermal Conductivity [W/mK]
1	0.5	0	16	1121	5.56	8.50	0.249
2		2	13	1107	4.54	8.41	0.254
3		4	10.5	1074	4.18	7.01	0.250
4	0.6	0	23	960	3.96	4.48	0.206
5		2	18	937	3.78	4.43	0.208
6		4	14	926	3.45	5.20	0.207
7		6	10.5	924	3.03	5.49	0.198
8	0.7	0	27	908	2.69	4.06	0.178
9		2	23	890	2.53	3.86	0.188
10		4	20	860	2.01	2.81	0.186
11		6	17.5	859	1.89	2.94	0.192
12		8	14	899	2.09	3.98	0.190
13		10	10,5	914	2.51	3.89	0.197

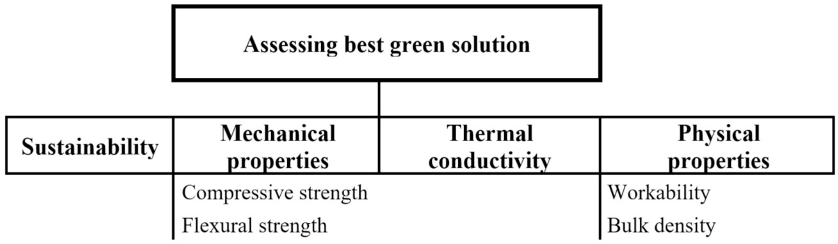

Fig. 8. AHP hierarchy tree.

Table 4
Pairwise comparison matrix and criteria weight.

	Sustainability	Thermal Conductivity	Bulk Density	Compressive Strength	Workability	Flexural Strength	Weight
Sustainability	1	1	1	5	4	5	0.252
Thermal Conductivity	1	1	1	8	7	7	0.315
Bulk Density	1	1	1	5	6	8	0.290
Compressive Strength	0.20	0.12	0.20	1	1	1	0.048
Workability	0.25	0.14	0.17	1	1	1	0.049
Flexural Strenght	0.20	0.14	0.12	1	1	1	0.045

where C′ and C″ denote the benefit and cost criteria sets, respectively.

(b) Compute the weighted and normalized Manhattan distance (S_i) and the weighted and normalized Chebyshev distance (Q_i) for each alternative P_i:

$$S_k = \sum_{i=1}^{n} \left[\frac{w_{ik} \bullet (g_i^* - g_{ki})}{(g_i^* - g_i^-)} \right] \quad \forall k \text{and } Q_k = \max_{\forall i} \left[\frac{w_i \bullet (g_i^* - g_{ki})}{(g_i^* - g_i^-)} \right] \quad \forall k \tag{5}$$

(c) Compute the aggregated index R_k for each alternative P_k:

$$R_k = \nu \bullet \frac{(S_k - S^*)}{(S^- - S^*)} + (1 - \nu) \bullet \frac{(Q_k - Q^*)}{(Q^- - Q^*)} \quad \forall k \tag{6}$$

where $S^* = \min_{\forall k} S_k$, $S^- = \max_{\forall k} S_k$, $Q^* = \min_{\forall k} Q_k$, $Q^- = \max_{\forall k} Q_k$.

The parameter $\nu \in [0,1]$ governs the decision-making orientation: values of $\nu > 0.5$ emphasize group utility, while values of $\nu < 0.5$ prioritize the minimization of individual regret. A balanced compromise solution, reflecting consensus, is achieved when $\nu = 0.5$. In this study we have considered the ν value equals to 0.5.

(a) Alternatives are ranked in ascending order based on the values of Sk, Qk, and Rk. The alternative ranked first according to Rk (i.e., P1) is considered the best compromise solution if it satisfies the following conditions:

(i) Acceptable advantage - $R(P_2 - P_1) \geq \frac{1}{n-1}$ where P_2 is the second-ranked alternative in the R_k list;
(ii) Acceptable stability - P_1 is also ranked first by S_k and/or Q_k.

If i. and/or ii. are not meet, a set of compromise solutions may be proposed:

- P_1 and P_2 if only ii. is violated;
- $\{P_1, P_2, \ldots, P_x\}$ if i. is violated, with P_x as the last solution in the R_k list for which $R(P_x - P_1) < \frac{1}{n-1}$.

For the case study, the criteria of sustainability, flexural strength, and compressive strength were to be maximized, while bulk density and thermal conductivity were to be minimized. As for workability, its score was represented using a triangular membership function, with the highest score assigned at 18 cm. The base of the triangle ranged from 10 cm to 30 cm, and any values outside this range received a score of zero. The final rankings based on these criteria are presented in Table 5:

Considering the conditions described at point d, the first two solutions can be regarded as having the same rank, namely mix n. 12 (ratio 0.7, WFW – 8 wt%) and 13 (ratio 0.7, WFW – 10 wt%). From a mathematical perspective, these solutions are optimal because they achieve the highest scores for the criteria with the greatest weights (i.e., sustainability, bulk density, and thermal conductivity). Moreover, it is possible to observe that the solutions with the highest W/P ratio values perform better compared to the others. Results from MCDM, are consistent with the mixes characterisation, considering the addition of the criterion "sustainability" that influences the final results (compromise solutions).

5. Sustainability and possible applications

The WFW-gypsum biocomposite proposed in this study represents an innovative technological solution that integrates environmental sustainability, application versatility, and improved performance compared to traditional gypsum-based plasters. A key novelty of this

Table 5
Ranking results of VIKOR.

ID	S	Q	R	RANK
1	0.8493	0.2943	0.9608	12
2	0.8370	0.3150	0.9897	13
3	0.7661	0.2984	0.8991	11
4	0.5007	0.2520	0.5895	10
5	0.4684	0.2016	0.4673	9
6	0.4254	0.1512	0.3361	6
7	0.3611	0.1008	0.1871	4
8	0.3201	0.2520	0.4385	8
9	0.3210	0.2016	0.3440	7
10	0.2639	0.1512	0.2011	5
11	0.2540	0.1008	0.0976	3
12	0.2512	0.0504	0.0000	1
13	0.2649	0.0788	0.0650	2

research lies in the possibility to modulate the W/B ratio, allowing the incorporation of a higher percentage of waste without compromising workability or significantly altering the setting time of gypsum (cf. section “2.3 Processing details”). This adaptability enables the novel biocomposite material to be tailored for various applications in construction, expanding its potential use in sustainable building solutions.

The integration of WFW into construction materials supports circular economy principles by reducing the use of virgin raw materials and diverting waste from landfills, with improved environmental and functional benefits. In addition, the use of gypsum-based mortars, which require lower production temperatures than most common hydraulic binders (e.g., cement-based materials), results in reduced energy consumption and CO_2 emissions. Overall, this approach provides an effective strategy for waste valorization, promoting sustainable material production and more environmentally responsible construction systems.

5.1. Technical classification of the developed biocomposite

Table 6 shows the classification of each formulation according to the class of resistance based on the measured UCS, as specified by EN 13279–1 [63].

The reference mixtures, free from WFW, achieved higher mechanical strength classifications (B5–B6), due to the greater cohesion of the gypsum matrix to loads. However, as the WFW content increased, a progressive reduction in strength was observed, leading to lower classifications ranging between B4 and B2, depending on the formulation. Despite such reduction, mixes with a moderate WFW content (W/B - 0.6, 2–4 wt%) maintained values consistent with B3–B4 classifications, making them suitable for non-structural applications such as plasters, coatings, and lightweight panels. This finding suggests that the optimization of WFW content could balance density reduction and mechanical performance, ensuring sustainable materials with good thermal insulation properties and a lower environmental impact. While mixes containing up to 4 wt% WFW fall within the B3–B4 classifications, those with more than 6 wt% exhibit a more pronounced UCS decrease, placing them in B2, which is characterized by limited load-bearing capacity. That indicates that, although incorporating WFW leads to a reduction in mechanical strength, it enables the development of lightweight materials, suitable for architectural finishes and non-structural components, offering benefits in terms of sustainability and thermal insulation.

5.2. Potential applications in the construction and design sector

Based on the physical, mechanical, and thermal properties discussed in this study, the developed WFW-gypsum biocomposite demonstrates strong potentials for various applications in construction. The resulting low densities and reduced thermal conductivities make this solution particularly suitable for non-structural elements, such as thermal insulating plasters, lightweight partition panels, and prefabricated components. Obtained results indicate that by optimizing the W/B ratio and adjusting the WFW content, it is possible to develop formulations that maintain adequate mechanical properties, while providing suitable energy efficiency, potentially adequate for green insulation systems. The observed low thermal conductivity indicates the material potential in lowering energy demand in buildings, aligning with sustainable construction strategies aimed at improving energy efficiency, as demanded by the present international requirements (i.e. European Green Deal, Building Energy Performance Standards). Additionally, the reduced density further supports the application in lightweight construction solutions, making them a promising alternative for modular and prefabricated components, where structural load reduction is a key requirement.

Beyond its functional advantages, the developed WFW-gypsum biocomposite also exhibits aesthetic characteristics that further expand potential applications in design and architecture, as shown in Fig. 9. The incorporation of wood particles within the gypsum matrix provides a natural, visually appealing slight texture, making these materials suitable for eco-friendly interior finishes, decorative wall panels, and furniture components. This aligns with the growing trend of biophilic design [64] which prioritizes natural textures and sustainable materials, increasingly sought after in contemporary architecture.

To further explore and visualize these applications, artificial intelligence (ChatGPT-4) was used to implement conceptual representations of possible building elements. Fig. 10 shows the potential integration of the developed biocomposite in various architectural and design contexts, highlighting its possible use in insulating panels, decorative architectural elements, and modular furniture solutions. This approach not only provides a clear depiction of its possible applications but also emphasizes the material's ability to combine functionality, sustainability, and aesthetics, positioning it as an innovative solution for more efficient, environmentally responsible, and circular construction.

Table 6
UCS values for each mortar and relative class of resistance according to EN 13279-1.

Specimen n.	W/B	B/A [wt%]	UCS [MPa]	Class of resistance
1		0	8.5	B6
2	0.5	2	6.2	B4
3		4	5.0	B3
4		0	7.8	B6
5	0.6	2	5.9	B4
6		4	4.8	B3
7		6	3.5	B2
8		0	7.2	B5
9		2	5.6	B4
10	0.7	4	4.2	B3
11		6	3.8	B2
12		8	3.4	B2
13		10	3.0	B2

6. Energy simulations

Based on the previous sections, developed materials improved energy performance and lightweight nature are key point for further development and insights. In particular, the following section will analyse possible applications as energy building materials in real contexts by implementing energy simulations on a building model.

Predicting the actual energy performance of a building, whether new or existing, is essential in guiding architects and engineers in selecting the most suitable materials and devices to use in order to improve the overall performance of a building, in light of nationals' laws and the Energy Performance of Buildings Directive [65]. To do that, energy simulation software are currently the tools most widely used by professionals to improve the quality of building design [3,49,66]. Essentially, an energy simulation represents a mathematical model of a building physical behaviour in terms of energy performance, concerning internal thermal comfort and, therefore, energy requirements for heating and/or cooling, together with other aspects such as the study of lighting, ventilation systems, and human comfort, all applied in specific climatic situations.

In this study, energy simulations were implemented using EnergyPlus™ (v. 25.2.0) [67], one of the most advanced and widely used software for dynamic energy modelling of buildings. EnergyPlus is an hourly and sub-hourly simulation software that allows detailed calculation of the thermal flows and energy balances of a building, taking into account complex interactions between the building envelope, systems, and climatic conditions [68]. To facilitate the creation of the architectural model, OpenStudio v. 2.0 was here used, an open-source graphical interface developed by the National Renewable Energy Laboratory (NREL), which allows to construct the building geometry, assign materials and stratigraphies, define the simulation conditions, and manage input/output data. OpenStudio also integrates the ASHRAE 90.1 standard library [69] to define usage profiles and internal loads, ensuring

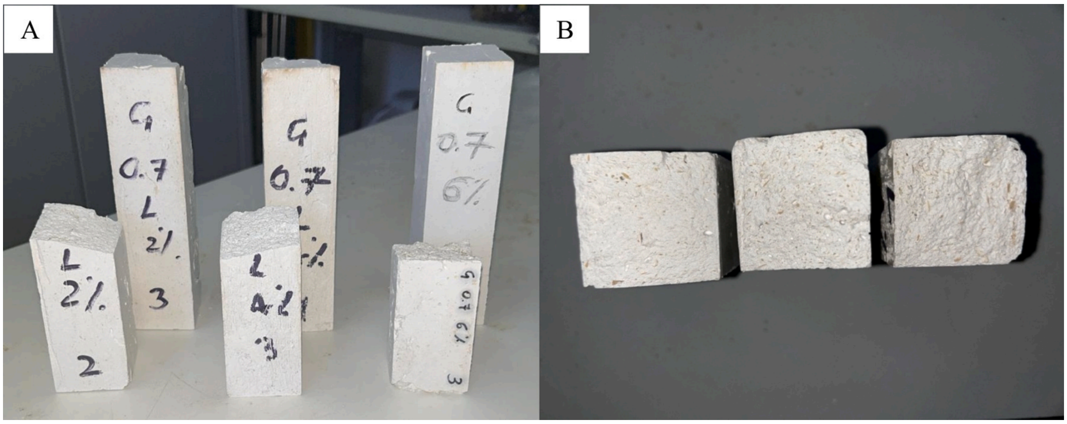

Fig. 9. Surface appearance of the developed biocomposites: (A) intact and fractured specimens produced with 2, 4, and 6 wt% WFW (W/B = 0.7); (B) fracture surfaces of the specimens, from left to right corresponding to 2, 4, and 6 wt% WFW (W/B = 0.7).

Fig. 10. Conceptual AI-generated visualisations of potential applications of the developed WFW–gypsum biocomposite (6% WFW, W/B = 0.7), highlighting the natural texture of the material for architectural instances. A - lightweight non-structural partition panels; B - interior wall finish. Images are provided for illustrative purposes only and do not represent validated engineering/architectural designs or real-scale prototypes.

consistency with international standards.

6.1. Model construction

The virtual model was developed to analyse the influence of experimental mortars applied as finishing layers on the energy performance of the building envelope. In this preliminary phase, a simplified building module was considered, consisting of a single rectangular room measuring 50.00 m^2 (5.00 × 10.00 m) and 3.00 m high, ideally located inside a tower building. This configuration allows the contribution of the vertical elements alone to be isolated: the four perimeter walls are exposed, while the floor and ceiling have been modelled as adiabatic to eliminate heat exchange upwards and downwards. The external walls have been fitted with six *fixed-window* windows, each measuring 1.5 m^2, distributed symmetrically on two opposite facades, corresponding to a total area of approximately 1/8 of the floor area. That was designed in accordance with the minimum requirement for the aero-illuminating ratio, as ruled by the Italian Ministerial Decree of 5 July 1975 on minimum sanitation requirements for housing, to ensure adequate lighting and ventilation for habitability [70]. Walls stratigraphy consists of load-bearing masonry made of 25.00 cm solid bricks (two-head disposition), covered internally with a 2.00 cm layer of experimental mortar and externally with a similar 3.00 cm layer. The remaining non-dispersive surfaces (floor and roof) were modelled in reinforced concrete and defined as adiabatic, so as not to influence the heat balance. In this preliminary study, a deep technological simplification was carried out, modelling the structure simply covered with layers of experimental plaster. That allows to isolate the influence of the developed mortars in terms of energy performance. Finally, the model was oriented so that each wall was perpendicular to one of the cardinal axes and located in the city of Rome, characterized by a Mediterranean climate with slight continental elements (Table 7). Winter in Rome is relatively mild during the day (~10 °C) but can reach temperatures of −2°/−4 °C at night; summer is hot and sunny, with highs above 30 °C and maximums up to 40 °C (climatic zone D according to the Italian D.P.R. n. 412 of 26–08-1993) [71]. The model internal conditions were set to ensure a comfort range between 20 °C and 26 °C.

The simulation period was one calendar year (1 January – 31 December), with hourly intervals (8760 h). Plant systems, insulating layers or additional technological devices were not introduced in order to keep conditions unchanged across all simulations.

The model has inevitable limitations; however, using the results of the basic configuration (conventional mortar) as a reference, it is possible to isolate the influence of the experimental mortars on overall energy performance. This preliminary approach provides useful information for further studies, in which complete stratigraphies and more complex scenarios will be considered.

6.2. Energy simulations

Thirteen building envelope configurations were considered, corresponding to the thirteen formulations developed and tested in this study. In all the simulations, the structural stratigraphy remained unchanged, while only the internal (2.00 cm) and external (3.00 cm) finishing plasters were varied. Table 8 shows the workplan (stratigraphies) for the analysed solutions.

Fig. 11 shows the simulations results of the annual energy demand, calculated for the virtual building model, obtained as the sum of the heating and cooling requirements according to the assessment criteria established by the international standards ISO 15927-1:2003 [72] and ISO 52016-1:2017 [73].

Simulation results show that a W/B ratio of 0.7 minimizes the energy demand necessary to keep indoor operative conditions stable within the defined thermal comfort range. In particular, formulations with W/B - 0.5 have the highest consumption, which remains almost constant as the quantity of added WFW increases. This behaviour suggests that, under these conditions, the changes introduced in the finishing layers have a marginal effect on the overall performance of the envelope. Solutions with W/B - 0.6, on the other hand, show a more complex trend: up to 4% WFW, energy demand remains almost constant, while at 6% there is a significant reduction, which represents the minimum value of the series.

Table 7
Average climatic conditions in Rome.

Month	Average temperature		Average daily irradiation hours
	Min [°C]	Max [°C]	
January	3	12	4
February	3	13	4.5
March	5	15	5.5
April	8	18	6.5
May	12	23	8.5
June	16	28	9.5
July	19	31	10.5
August	19	31	9.5
September	16	27	8
October	12	22	6.5
November	8	16	4.5
December	5	12	3.5

Table 8
Workplan stratigraphies for the simulated solutions.

Solution n.	Inner finishing (2 cm)	Structure (25 cm)	Outer finishing (3 cm)
1	W/B 0.5–0 wt%		W/B 0.5–0 wt%
2	W/B 0.5–2 wt%		W/B 0.5–2 wt%
3	W/B 0.5–4 wt%		W/B 0.5–4 wt%
4	W/B 0.6–0 wt%		W/B 0.6–0 wt%
5	W/B 0.6–2 wt%		W/B 0.6–2 wt%
6	W/B 0.6–4 wt%	Red brick	W/B 0.6–4 wt%
7	W/B 0.6–6 wt%	(two head	W/B 0.6–6 wt%
8	W/B 0.7–0 wt%	disposition)	W/B 0.7–0 wt%
9	W/B 0.7–2 wt%		W/B 0.7–2 wt%
10	W/B 0.7–4 wt%		W/B 0.7–4 wt%
11	W/B 0.7–6 wt%		W/B 0.7–6 wt%
12	W/B 0.7–8 wt%		W/B 0.7–8 wt%
13	W/B 0.7–10 wt%		W/B 0.7–10 wt%

However, even in this case, consumption remains higher than the corresponding formulations with W/B - 0.7. Formulations with W/B - 0.7 are the best performers, as they show the lowest energy demand values. Within this series, however, there is an upward trend with increasing WFW, leading to a progressive deterioration in performance up to 10%.

These results are in line with the experimental thermal conductivity values (cf. Fig. 7), as denser mixtures with higher λ (W/B – 0.5) tend to be associated with higher consumption, while the reduction in λ, as observed in some intermediate formulations, is reflected in improved energy performance. However, the increasing trend observed for W/B – 0.7 shows that overall efficiency does not depend exclusively on conductivity, but on the balance between insulation and the dynamic thermal behaviour of the building envelope. Therefore, for the considered climatic conditions in Rome, configurations with W/B – 0.7 resulted the most advantageous from an energy point of view, despite showing a progressive worsening as the addition of WFW increases.

6.3. Comparison with commercial gypsum-based materials

To further contextualize the performance of the developed WFW–gypsum biocomposite, a comparative analysis with selected commercial gypsum-based products was carried out considering density and thermal conductivity, as the most relevant Key Performance Indicators (KPI) for lightweight non-structural building energy materials. Commercial solutions commonly employed for lightweight partitions, wall linings, and indoor finishing systems were selected from Environmental Product Declarations (EPDs) and technical datasheets. For confidentiality reasons, and to avoid explicitly mentioning commercial trademarks, the considered commercial products were anonymized and identified as "Product 1–4".

The formulation W/B = 0.7 with 6 wt% WFW was previously selected (cf. Section 4: 4. Selection of the best formulation by means of multicriteria approaches) as optimal configuration due to its balanced compromise between lightweight behaviour, thermal insulation performance, and practical applicability in building systems.

Fig. 12 shows the comparison between the individuated developed WFW–gypsum biocomposite and selected commercial gypsum-based products, whose density and thermal conductivity were clearly stated and certified in technical datasheets. Fig. 12A shows the comparison in term of material bulk density. Results indicated that the considered experimental formulation exhibits an intermediate density values compared to the analysed commercial solutions. In particular, Products 1, 3, and 4 showed higher densities, associated with more compact and reinforced gypsum-based systems, whereas Product 2 exhibited the lowest value among the considered materials. Nevertheless, the developed biocomposite maintained a relatively low density, confirming its suitability for lightweight non-structural applications.

Fig. 12B shows the comparison feature based on thermal conductivity. It is noted that the developed experimental formulation exhibits

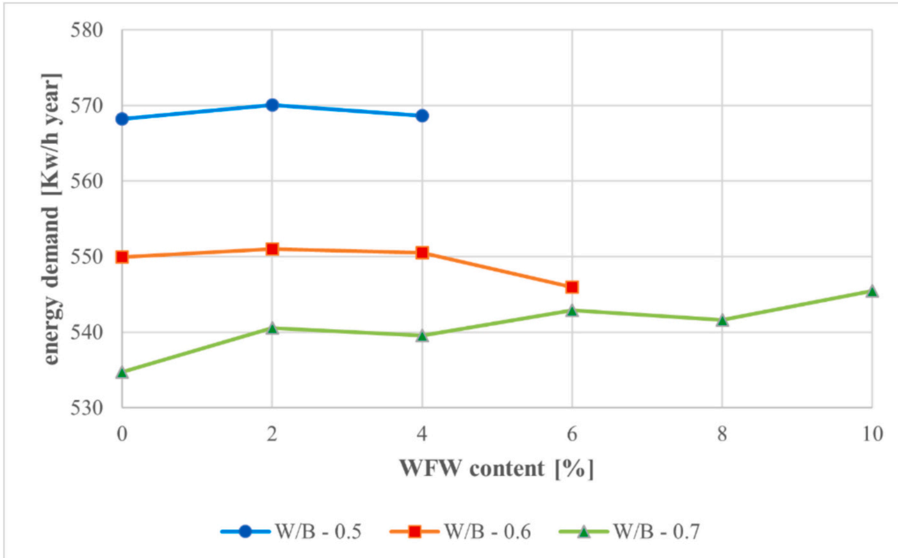

Fig. 11. Simulated annual energy consumption.

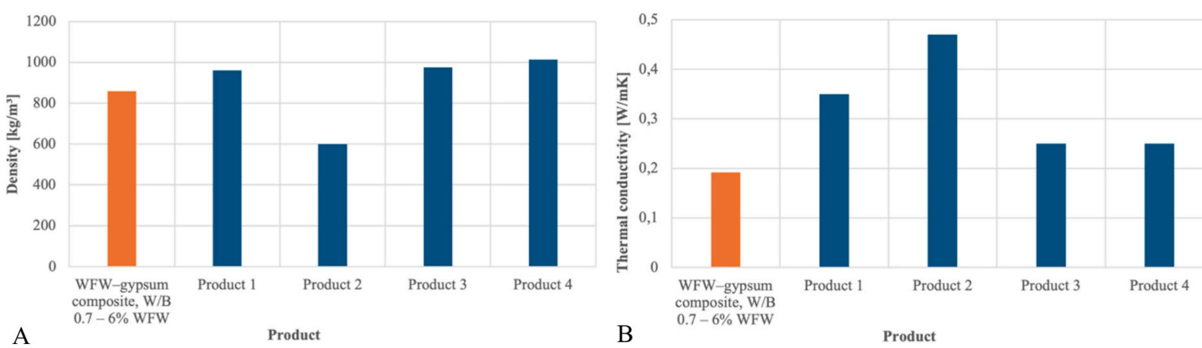

Fig. 12. Comparison between the developed WFW–gypsum biocomposite (W/B = 0.7, 6 wt% WFW) and selected commercial gypsum-based products in terms of density (A) and thermal conductivity (B). Commercial products were anonymized for comparison purposes: Product 1 = fibre-reinforced gypsum panel; Product 2 = lightweight gypsum ceiling panel; Product 3 = high-density gypsum board with wood and glass fibres; Product 4 = glass-fibre reinforced gypsum board.

the lowest λ value among all the compared materials. While the analysed commercial products showed conductivity values ranging between approximately 0.25 and 0.47 W/mK, the developed WFW–gypsum biocomposite reached a value close to 0.19 W/mK. This behaviour is consistent with the reduced density of the material and with the incorporation of lignocellulosic waste within the gypsum matrix, resulting in highly improved insulating performance. Overall, the obtained results highlight that the developed biocomposite exhibits extremely competitive thermal insulation behaviour together with relatively low density values, suggesting its possible applicability in lightweight indoor gypsum-based systems.

7. Conclusions

This study demonstrated the feasibility of developing novel sustainable gypsum–wood biocomposite by reusing industrial wood waste as an alternative aggregate. The considered waste was reused without any pre-treatment, and testing specimens were developed following a standardized and easy manufacturing procedure ensuring a simple and scalable production process compatible with conventional gypsum-based formulations.

In particular, the conducted analysis revealed that the incorporation of WFW in gypsum composites affects both density and mechanical performance in a closely related manner. Reductions in density, arising from the lower density of the wooden fibres and the increased porosity of the matrix, are generally accompanied by decreases in mechanical strength, particularly in mixtures with high W/B ratios. Nevertheless, at higher waste contents, a partial recovery of both density and mechanical strength is observed, indicating that the fibres contribute to a filler effect that improves packing the matrix, mitigating eventual performance loss. The observed thermal conductivity showed that the incorporation of WFW contributes to improve the insulating performance of the biocomposite, particularly at higher W/B ratios where porosity is greater. While denser mixtures (W/B = 0.5) maintain higher conductivity due to the dominance of the continuous gypsum matrix, lower density composites (W/B = 0.7) exhibit markedly reduced values, highlighting the beneficial role of the waste in limiting heat transfer. That was also confirmed by the multi-criteria analysis and the energy simulations.

These findings confirm that the incorporation of WFW significantly influences the overall behaviour of gypsum-based composites, affecting all the functional characteristics with particular reference to density, mechanical performance, and thermal insulation properties, simultaneously. From a sustainability perspective, the obtained results support the potential reuse of WFW as a secondary raw material for gypsum-based applications, provided that the balance between binder content, fibre proportion, and water demand is carefully optimized.

From the analyses and the comparison with the technical standard, all the developed formulations resulted suitable for lightweight non-structural applications in construction. Moreover, the observed reduced thermal conductivity makes the developed biocomposites potentially suitable for energy applications in construction, such as lightweight insulating plasters, panels, and indoor finishing components.

Overall, the reuse of industrial wood waste within gypsum-based materials is consistent with circular economy strategies aimed at reducing waste disposal and limiting the consumption of virgin raw materials. In this context, the developed biocomposites may represent a promising approach for the development of more sustainable and resource-efficient building materials, in line with European sustainability strategies.

8. Future research

Future research will include more detailed energy simulations expanding the climatic conditions and better capturing the dynamic thermo-physical behaviour of the building system and, hence, refine the accuracy of energy demand predictions to wider geographical contexts for practical applicability under different operating conditions. Other studies will focus on Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analyses to quantify the environmental and economic implications of the developed biocomposites compared to conventional gypsum-based materials. Additional investigations will address long-term durability aspects under environmental stressors, including hygrothermal behaviour, moisture absorption, freeze–thaw resistance, ageing performance, and environmental exposure conditions, which are essential for the evaluation of the materials' applicability in the long-term period and in real construction scenarios. That will also help investigating industrial scalability, including feedstock availability, material consistency, production cost implications, and process feasibility under larger-scale production conditions that will be detailed in following publications.

Authors contribution

M. Saeli handled the methodology and the scientific plan; R. Leone and A. Calà produced and tested the specimens; R. Leone and M. Saeli discussed the experimental results; M.N. Capela conducted and discussed the waste characterization; G. La Scalia implemented the MCDM; A. Calà managed the energy simulations; T. Campisi and M. Saeli oversaw the scientific coordination. All the authors were involved in the manuscript preparation.

CRediT authorship contribution statement

Manfredi Saeli: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Rosanna Leone:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Giada La Scalia:** Writing – original draft, Investigation, Formal analysis. **Adriana Calà:** Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis. **Marinélia N.Capela:** Writing – original draft, Investigation, Formal analysis. **Tiziana Campisi:** Writing – original draft, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 4.0 in order to solely produce visual images of possible building elements using the developed biocomposite (Fig. 10). After using this tool/service, the authors verified, reviewed, and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Acknowledgements

The company Sicilgesso S.p.A., plant in Calatafimi Segesta (Sicily), is thanked for furnishing the gyspum. The company Chimenti Legnami S. A.S di Lucchese P. e Marabeti I. & C., Partinico (Sicily) is thanked for furnishing the fir WFW. T. Campisi, G. La Scalia M., R. Leone, and M. Saeli, would like to acknowledge the Project “3A- ITALY - FORWARD”, Spoke 4: Smart and sustainable materials for circular and augmented industrial products and processes, Project code PE00000004, Concession Decree No. 341 of 15.3.2022 adopted by the Italian Ministry of University and Research (Ministero dell'Università e della Ricerca - MUR), CUP B73C22001270006, funded by the European Union – NextGenerationEU. A. Calà would like to acknowledge the Project “Network 4 Energy Sustainable Transition — NEST”, Spoke 8: Final use optimization, sustainability & resilience in energy supply chain, Project code PE0000021, Concession Decree No. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP B73C22001280006. Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 341 of 15.03.2022 of MUR; funded by the European Union – NextGenerationEU. M. Capela would like to acknowledge the project CICECO Aveiro Institute of Materials, UID/50011/2025 (DOI 10.54499/UID/50011/2025) & LA/P/0006/2020 (DOI 10.54499/LA/P/0006/2020), financed by national funds through the FCT/MCTES (PIDDAC).

Data availability

Data will be made available on request.

References

[1] European Environment Agency (EEA), Greenhouse Gas Emissions From Energy, Available at: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy, 2024.
[2] Reuters, Why the Building Sector Needs A Make-Do-And-Mend Mentality, Available at: https://www.reuters.com/sustainability/climate-energy/why-building-sector-needs-make-do-mend-mentality-2024-05-02, 2024.
[3] M. Saeli, M.N. Capela, T. Campisi, M.P. Seabra, D.M. Tobaldi, C.M. La Fata, Architectural technologies for life environment: spent coffee ground reuse in lime-based mortars. A preliminary assessment for innovative green thermo-plasters, Constr. Build. Mater. 319 (2022) 126079, https://doi.org/10.1016/j.conbuildmat.2021.126079.
[4] United Nations environment programme (UNEP), Global Status Report for Buildings and Construction, Available at, https://asvis.it/notizie/2-20336/edilizia-sostenibile-ampio-gap-tra-stato-attuale-e-percorso-di-decarbonizzazione, 2022.
[5] UNEP (United Nations Environment Programme), Global Waste Management Outlook 2024, Available at: https://www.unep.org/resources/global-waste-management-outlook-2024, 2024.
[6] R. Leone, A. Calà, M.N. Capela, S. Colajanni, T. Campisi, M. Saeli, Recycling mussel shells as secondary sources in green construction materials: a preliminary assessment, Sustainability 15 (2023) 3547, https://doi.org/10.3390/su15043547.
[7] A. Besserer, S. Troilo, P. Girods, Y. Rogaume, N. Brosse, Cascading recycling of wood waste: a review, Polymers 13 (2021) 1752, https://doi.org/10.3390/polym13091752.
[8] A. Yayla, A.R. Mason, J. Wang, S. van Ewijk, R.J. Myers, Global wood harvest is sufficient for climate-friendly transitions to timber cities, Nat. Sustainability 8 (2025) 1013–1025, https://doi.org/10.1038/s41893-025-01605-w.
[9] FAO, Global Forest Products Facts and Figures, 2023, Available at: https://www.fao.org/forestry/statistics, 2023.
[10] Rilegno, Giving new life to wooden packaging, Available at, https://www.renewablematter.eu/en/giving-new-life-to-wooden-packaging, 2023.
[11] R. Leone, T. Campisi, M. Saeli, Wood industry wastes valorisation and reuse for a greener architecture, in: R. Corrao, T. Campisi, S. Colajanni, M. Saeli, C. Vinci (Eds.), Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering). Colloqui.AT.E 2024 611, Springer, Cham, 2025, pp. 439–455, https://doi.org/10.1007/978-3-031-71863-2_28. Lecture Notes in Civil Engineering.
[12] M.I. Shahidul, M.L. Malcolm, M.S.J. Hashmi, M.H. Alhaji, Waste resources recycling in achieving economic and environmental sustainability: review on wood waste industry, in: S. Hashmi, I.A. Choudhury (Eds.), Encyclopedia of Renewable and Sustainable Materials, Elsevier, 2020, pp. 965–974. ISBN 9780128131961, https://doi.org/10.1016/B978-0-12-803581-8.11275-5.

[13] A. Romaní, P.G. Del-Río, A. Rubira, M.G. Pérez, G. Garrote, Co-valorization of discarded wood pinchips and sludge from the pulp and paper industry for production of advanced biofuels, Ind. Crop. Prod. 209 (2024) 117992, https://doi.org/10.1016/j.indcrop.2023.117992.

[14] R. Leone, G. La Scalia, M. Saeli, A critical review on reuse potentials of wood waste for innovative products and applications: trends and future challenges, Sustainable Futures 10 (2025) 100869, https://doi.org/10.1016/j.sftr.2025.100869.

[15] Y.M. Leng, X. Zhao, T. Fu, X.L. Wang, Y.Z. Wang, Bio-based flame-retardant and smoke-suppressing wood plastic composites enabled by phytic acid tyramine salt, ACS Sustain. Chem. Eng. 10 (5) (2022) 5055–5066, https://doi.org/10.1002/pc.27549.

[16] V. Ferrari, M.T. Nazari, N.F. da Silva, L. Crestani, L.M. Raymundo, G.L. Dotto, J. S. Piccin, L.F.S. Oliveira, A.M. Bernardes, Pyrolysis: a promising technology for agricultural waste conversion into value-added products, Environ. Dev. Sustain. 27 (2025) 17957–17991, https://doi.org/10.1007/s10668-024-04760-w.

[17] M.A. Pedreño-Rojas, C. Porras-Amores, P. Villoria-Sáez, M.J. Morales-Conde, I. Flores-Colen, Characterization and performance of building composites made from gypsum and woody-biomass ash waste: a product development and application study, Constr. Build. Mater. 419 (2024) 135435, https://doi.org/10.1016/j.conbuildmat.2024.135435.

[18] B. Gagnon, X. Tanguay, B. Amor, A.F. Imbrogno, Forest products and circular economy strategies: a Canadian perspective, Energies 15 (3) (2022) 673, https://doi.org/10.3390/en15030673.

[19] M. Saeli, D.M. Tobaldi, M.P. Seabra, J.A. Labrincha, Mix design and mechanical performance of geopolymeric binders and mortars using biomass fly ash and alkaline effluent from paper-pulp industry, J. Clean. Prod. 208 (2019) 1188–1197, https://doi.org/10.1016/j.jclepro.2018.10.213.

[20] M. Saeli, L. Senff, D.M. Tobaldi, J. Carvalheiras, M.P. Seabra, J.A. Labrincha, Unexplored alternative use of calcareous sludge from the paper-pulp industry in green geopolymer construction materials, Constr. Build. Mater. 246 (2020) 118457, https://doi.org/10.1016/j.conbuildmat.2020.118457.

[21] M. Saeli, G. Galluccio, R. Leone, P. Nicholas, M. Tamke, Experimenting bioprinting for wood waste upcycling in architecture and design preliminary assessments and application scenarios, in: Lecture Notes in Civil Engineering 766, 2025, pp. 766–789, https://doi.org/10.1007/978-3-032-06993-1_43.

[22] A. Calà, M.N. Capela, S. Colajanni, M.P. Seabra, M. Saeli, Review on the potential of olive waste reuse and valorisation for innovative green building solutions, in: Lecture Notes in Civil Engineering 765, 2025, pp. 98–117, https://doi.org/10.1007/978-3-032-06978-8_6.

[23] R. Leone, L. Lombardo, F. Marchese Ragona, T. Campisi, M. Saeli, Upcycling Arundo donax biomass: a systematic review of applications, materials, and environmental benefits for greener construction, Sustainability 17 (16) (2025) 7402, https://doi.org/10.3390/su17167402.

[24] Z. Jiang, Invasive alien species (IAS) spread, impact and management, Theore. Nat. Sci. 7 (2023) 26–32, https://doi.org/10.54254/2753-8818/7/20230110.

[25] Y. Feng, Z. Xue, H. Zhong, B. Zhang, J. Yang, J. Xie, Improving geopolymer concrete performance with hazardous solid waste phosphogypsum, J. Build. Eng. 95 (2024) 110333, https://doi.org/10.1016/j.jobe.2024.110333.

[26] Y. Feng, Z. Xue, B. Zhang, J. Xie, C. Chen, J. Tan, C. Zhao, Effects of phosphogypsum substitution on the performance of ground granulated blast furnace slag/fly ash-based alkali-activated binders, J. Build. Eng. 70 (2023) 106387, https://doi.org/10.1016/j.jobe.2023.106387.

[27] A. Ranesi, P. Faria, M.T. Freire, M. Gonçalves, R. Veiga, Eco-efficient plastering mortars for improved indoor comfort – the influence of *Acacia dealbata* bark addition, Constr. Build. Mater. 421 (2024) 135572, https://doi.org/10.1016/j.conbuildmat.2024.135572].

[28] A. Ranesi, P. Faria, R. Correia, M.T. Freire, R. Veiga, M. Gonçalves, Gypsum mortars with *Acacia dealbata* biomass waste additions: effect of different fractions and contents, Buildings 12 (3) (2022) 339, https://doi.org/10.3390/buildings12030339.

[29] European Commission, The European Green Deal: Striving to be the First Climate-Neutral Continent, available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en, 2024.

[30] M. Saeli, M.N. Capela, C. Piccirillo, D.M. Tobaldi, M.P. Seabra, F. Scalera, R. Striani, C. Esposito Corcione, T. Campisi, Development of energy-saving innovative hydraulic mortars reusing spent coffee ground for applications in construction, J. Clean. Prod. 399 (2023) 136664, https://doi.org/10.1016/j.jclepro.2023.136664.

[31] M. Saeli, R. Micale, M.P. Seabra, J.A. Labrincha, G. La Scalia, Selection of novel geopolymeric mortars for sustainable construction applications using fuzzy topsis approach, Sustainability 12 (15) (2020) 5987, https://doi.org/10.3390/su12155987.

[32] S. Cascone, R. Micale, M. Saeli, Upcycling volcanic ash from Mount Etna for green roof system: a circular strategy for energy-efficient and sustainable buildings, J. Build. Eng. 118 (2026) 115070, https://doi.org/10.1016/j.jobe.2025.115070.

[33] European Union, European Commission, A European Green Deal: Striving to be the First Climate-Neutral Continent, Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en, 2024.

[34] European Commission, A renovation wave for Europe – greening our buildings, creating jobs, improving lives, Communication COM (2020), 662 final. Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/renovation-wave_en.

[35] United Nations, Transforming our world: the 2030 agenda for sustainable development. Resolution A/RES/70/1, Available at: http://sdgs.un.org/2030agenda, 2015.

[36] European Commission, Commission Decision 2000/532/EC of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes, Off. J. Eur. Communities L (226) (2000) 3–24. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32000D0532s.

[37] UNI EN 13279–2, Gypsum binders and gypsum plasters - Part 2: Test methods, 2014.

[38] EN 1015–3, Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table), 1999.

[39] UNI EN 12667, Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of medium and high thermal resistance, 2002.

[40] D. Ferrández, M. Álvarez, A. Zaragoza-Benzal, Á. Cobo-González, P. Santos, Development and characterization of innovative hemp–gypsum composites for application in the building industry, Appl. Sci. 14 (6) (2024) 2229, https://doi.org/10.3390/app14062229.

[41] B. Bencsik, L. Denes, E.M. Sosa, C. Hassler, G. Oporto, J. Norris, J. McNeel, Flexural properties evaluation of homogeneous and hybrid hardwood cross-laminated timber (CLT): a comparative analysis using destructive and non-destructive methods, Case Stud. Constr. Mater. 22 (2025) e04673, https://doi.org/10.1016/j.cscm.2025.e04673.

[42] M. Ouda, A.A. Abu Sanad, A. Abdelaal, A. Krishna, M. Kandah, J. Kurdi, A comprehensive review of sustainable thermal and acoustic insulation materials from various waste sources, Buildings 15 (16) (2025) 2876, https://doi.org/10.3390/buildings15162876.

[43] A. Rahman, M.A.H. Khondoker, Effect of treatment methods on material properties and performance of sawdust-concrete and sawdust-polymer composites, Polymers 16 (23) (2024) 3289, https://doi.org/10.3390/polym16233289.

[44] S.V. Vassilev, D. Baxter, L.K. Andersen, C.G. Vassileva, An overview of the chemical composition of biomass, Fuel 89 (2010) 913–933, https://doi.org/10.1016/j.fuel.2009.10.022.

[45] S.V. Vassilev, D. Baxter, L.K. Andersen, C.G. Vassileva, T.J. Morgan, An overview of the organic and inorganic phase composition of biomass, Fuel 94 (2012) 1–33, https://doi.org/10.1016/j.fuel.2011.09.030.

[46] X. Zhang, L. Li, F. Xu, Chemical characteristics of wood Cell Wall with an emphasis on ultrastructure: a mini-review, Forests 213 (3) (2022) 439, https://doi.org/10.3390/f13030439.

[47] X. Zhao, Y. Liu, L. Zhao, et al., A scalable high-porosity wood for sound absorption and thermal insulation, Nat. Sustainability 6 (2023) 306–315, https://doi.org/10.1038/s41893-022-01035-y.

[48] M. Ichim, E.I. Muresan, E. Codau, Natural-Fiber-reinforced polymer composites for furniture applications, Polymers 16 (22) (2024) 3113, https://doi.org/10.3390/polym16223113.

[49] L. Lombardo, M.N. Capela, T. Campisi, M. Saeli, Development of green energy-saving biocomposite thermoplaster upcycling Prunus amygdalus waste: a preliminary assessment in mountain road guard house, Energ. Buildings 344 (2025) 115937, https://doi.org/10.1016/j.enbuild.2025.115937.

[50] T.L. Saaty, How to make a decision: the analytic hierarchy process, Eur. J. Oper. Res. 48 (1) (1990) 9–26, https://doi.org/10.1016/0377-2217(90)90057-.

[51] T.L. Saaty, Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process, Analytic Hierarchy Process Series 6, RWS Publications, Pittsburgh, 2000.

[52] S. Opricovic, Multi-Criteria Optimization of Civil Engineering Systems, PhD Thesis, 302, Faculty of Civil Engineering, Belgrade, 1998.

[53] J. Goers, M. Eckart, G. Horton, CMAA–AHP: combinatorial multicriteria acceptability analysis with the analytic hierarchy process, CEJOR (2024), https://doi.org/10.1007/s10100-024-00936-x.

[54] T.L. Saaty, The Analytic Network Process, RWS Publications, Pittsburgh, 1996.

[55] C.M. La Fata, A. Giallanza, R. Micale, G. La Scalia, Ranking of occupational health and safety risks by a multi-criteria perspective: inclusion of human factors and application of VIKOR, Saf. Sci. 138 (2021) 1–11, 105234, https://doi.org/10.1016/j.ssci.2021.105234.

[56] L. Bodin, S.I. Gass, On teaching the analytic hierarchy process, Comput. Oper. Res. 30 (10) (2003) 1487–1497, https://doi.org/10.1016/S0305-0548(02)00188-0.

[57] N. Pankratova, N. Nedashkovskaya, Methods of evaluation and improvement of consistency of expert pairwise comparison judgements, Int. J.: Inform. Theories Appl. 22 (3) (2015) 203–223.

[58] W. Koczkodaj, A new definition of consistency of pairwise comparisons, Math. Comput. Model. 18 (7) (1993) 79–84, https://doi.org/10.1016/0895-7177(93)90059-8.

[59] A. Salo, R. Hamalainen, On the measurement of preference in the analytic hierarchy process, J. Multi-Criteria Decis. Anal. 6 (6) (1997) 309–319, https://doi.org/10.1002/(SICI)1099-1360(199711)6:6%3C309::AID-MCDA163%3E3.0.CO;2-2.

[60] G. Crawford, C. Williams, A note on the analysis of subjective judgment matrices, J. Math. Psychol. 29 (4) (1985) 387–405, https://doi.org/10.1016/0022-2496(85)90002-1.

[61] S. Pant, A. Kumar, M. Ram, Y. Klochkov, H.K. Sharma, Consistency indices in analytic hierarchy process: a review, Mathematics 10 (8) (2022) 1206, https://doi.org/10.3390/math10081206.

[62] Y. Lee, M.C.L. Lee, Y.J. Kim, Barriers and strategies of hydrogen fuel cell power generation based expert survey in South Korea, Int. J. Hydrog. Energy 47 (2022) 5709–5719, https://doi.org/10.1016/j.ijhydene.2021.11.212.

[63] EN 13279–1, Gypsum binders and gypsum plasters - Part 1: Definitions and requirements, 2008.

[64] W.D. Browning, C.O. Ryan, Biophilic design with wood in British Columbia, Forestry Innovation Investment Ltd, 2024. Available at: https://www.terrapinbg.com/report/biophilic-design-wood-bc.

[65] European Commission, Energy performance of buildings directive (EPBD), EU/2024/1275 (2024), available at: https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng.

[66] M. Saeli, C. Piccirillo, I.P. Parkin, R. Binions, I. Ridley, Energy modelling studies of thermochromic glazing, Energ. Buildings 42 (2010) 1666–1673, https://doi.org/10.1016/j.enbuild.2010.04.010.

[67] U.S. Department of Energy, National Laboratory of the Rockies, EnergyPlus, available at, https://energyplus.net/, 2026.

[68] D.B. Crawley, L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, R.K. Strand, R.J. Liesen, D.E. Fisher, M.J. Witte, J. Glazer, EnergyPlus: creating a new-generation building energy simulation programme, Energ. Buildings 33 (4) (2001) 319–331, https://doi.org/10.1016/S0378-7788(00)00114-6.

[69] ASHRAE, Standard 90.1, Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings, available at, https://www.ashrae.org/technical-resources/bookstore/standard-90-1, 2022.

[70] Ministerial Decree of 5 July 1975, Modifications to the ministerial instructions of 20 June 1896 regarding the minimum height and the main hygienic-sanitary requirements of dwelling spaces, Official Gazette of the Italian Republic, No. 190 (1975) available at: https://www1.prefettura.it/FILES/AllegatiPag/1195/7DM_Sanit_05_luglio_1975-posti_CAS.pdf.

[71] Italian Republic, Presidential Decree n. 412 of 26 August 1993, Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, Gazzetta Ufficiale della Repubblica Italiana 231, 1993.

[72] International Organization for Standardization (ISO) / European Committee for Standardization (CEN), Heating and cooling of buildings – Climatic data – Part 1: Monthly means for evaluation of energy need for space heating and cooling and methods for splitting global solar irradiance into the direct and diffuse parts and for calculating the solar irradiance on tilted plane, 2003.

[73] International Organization for Standardization (ISO), Energy performance of buildings – Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads – Part 1: Calculation procedures, ISO 52016-1, 2017.

Glossary

AHP: Analytic Hierarchy Process
BR: Bending Resistance
CI: Consistency Index
CR: Consistency Ratio
EPDs: Environmental Product Declarations
EWC: European Waste Catalogue
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
MCDM: Multi-Criteria Decision Making
RH: Relative Humidity
RI: Random Index
SDGs: Sustainable Development Goals
SEM: Scanning Electron Microscopy
UCS: Uniaxial Compressive Strength
VIKOR: VIseKriterijumska Optimizacija I Kompromisno Resenje
W/B: Water-to-Binder ratio
WFW: Wood Fibre Waste
XRD: X-ray Diffraction
XRF: X-ray Fluorescence