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Spent Coffee Grounds-Based Thermoplaster System to Improve Heritage Building Energy Efficiency: A Case Study in Madonie Park in Sicily

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Abstract: This study reports on the application of an innovative plastering system that reuses organic waste, namely spent coffee grounds (SCG), to improve energy efficiency in historical buildings according to the European Green Deal. The case study was conducted in the village of Polizzi Generosa, selected from 21 small villages located in the extensive UNESCO Geopark of Madonie Park in Sicily. Over time, traditional plasters used in Madonie buildings have shown durability issues due to thermal and hygrometric stresses caused by significant temperature fluctuations in the area. Moreover, much of the considered architectural heritage lacks energy efficiency. Given the global increase in coffee production and the need for more sustainable waste management systems, this investigation proposes an ecological method to reuse SCG in plaster formulation, thereby enhancing the circular economy. To achieve this, many thermoplaster formulations were developed, and the best-performing one, considering both material and aesthetic compatibility with historical buildings, was selected for a real-world application. Additionally, virtual modeling and energy simulations were conducted to test the energy performance of a traditional building in Polizzi Generosa using SCG-based thermoplaster in comparison to traditional lime mortar and commercial alternatives. The real-world application demonstrated the technical feasibility of the process, and the energy simulations showed an improved building masonry energy performance of 0.788 W/m^2K and an 11% improvement compared to traditional plaster. Results clearly indicate that SCG can be successfully reused to produce eco-friendly bio composite plasters, providing a more sustainable housing option. This approach offers a durable and cost-effective alternative for housing solutions that meet regulatory requirements for energy efficiency, serving as a smart, highly sustainable, and long-lasting choice for the construction sector. Finally, this result supports the research goal of transforming the 21 municipalities of Madonie into smart and green villages, with the "Smart Coffee-House" exemplifying intelligent rehabilitation processes of existing heritage buildings.

Keywords: spent coffee grounds; bio composite mortar; thermoplaster; green building technology; Madonie smart villages; smart rehabilitation

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1. Introduction

The Madonie mountains is an inner rural area, which comprises 21 small municipalities, and lies in the heart of the Mediterranean and Sicily, just a few kilometers from the regional capital, Palermo [1]. In 1989, the mountainous area was designated as a "Park" by the Sicilian Government to safeguard its uniqueness, and in 2015, it was recognized as a UNESCO Geopark, thanks to its stunning views, unique flora and fauna, majestic trees, idyllic villages, and the warm hospitality of its residents.

Madonie Park is characterized by a great diversity of flora and fauna—unique in Sicily and the Mediterranean basin—with over 1600 documented plant species across 40,000 hectares [2,3]. Despite the potential, the little municipalities have been affected by a deep depopulation in the last few decades. In fact, approximately 60% of the population moved to Northern Italy or to the large smart cities in search of job opportunities, services, and a better standard of life [4]. Hence, the Madonie area presently needs a huge regeneration approach to improve the quality of life, recover the traditional values, establish tourist circuits, and implement architectural heritage to become attractive again, blending tradition with innovation in a smart and innovative way. Among the regeneration strategies, the rehabilitation of existing traditional architecture is fundamental to achieve a green upscale of the inner villages and make them smarter [5,6]. Addressing these challenges requires innovative approaches that combine environmental sustainability with heritage conservation to enhance the existing asset, making it livable and attractive for repopulation [7].

Another challenge to be faced is energy improvement in the existing buildings in light of the EU "Renovation Wave" [8]. Indeed, about 75% of EU buildings are highly inefficient and urgently require rehabilitation to improve energy efficiency [9]. This is aligned with the United Nations Sustainable Development Goals (SDGs) [10] and is in response to the strategies for the implementation of the construction sector, supported by substantial financial investments [11,12].

In Italy, numerous strategies have already been implemented to improve the existing housing stock, redevelop buildings in a state of abandonment, and, hence, push the property market to reclaim the cultural identity of small, abandoned centers. For instance, homes were sold for a symbolic price of 1€, providing a "super bonus" tax exemption for buyers that covers 110 percent of qualifying building expenditures, but with an obligation to recover and refurbish the building [13]. Other effective initiatives were energy efficiency implementation strategies like the "super bonus" and "eco bonus" initiatives. [14–16]. Concrete assistance was also supported by the National Recovery and Resilience Plan (PNRR) [17], the National Strategy for Inner Areas [18], and the National Strategy for Italian Mountains [19]. These European and Italian policies have facilitated these regions with financial resources and opportunities to implement smart, innovative strategies and technologies for rehabilitating and recovering existing heritage buildings.

This paper discusses the application of innovative and sustainable materials to improve the energy performance of traditional buildings and also valorize local resources in light of the circular economy approach, which successfully blends tradition and innovation.

The construction sector, due to its high consumption of non-renewable resources, greenhouse gas emissions, and waste production, is deemed unsustainable. For instance, the cement industry alone annually surpasses 4 billion tons of CO_2, significantly contributing to emissions [9]. Therefore, it is crucial to develop more environmentally friendly and efficient alternative materials, optimize the use of secondary cementitious resources, promote waste integration [20,21], and adopt economically advantageous sustainable production processes [22] and also include the possibility of reusing local products such as organic municipal waste or scraps. Moreover, global industrial activity generates a significant amount of waste annually, and prudent management of that waste could lead to financial benefits, reduced environmental impact, and an increased circular economy by maximizing reuse as an alternative to conventional disposal. This approach could effectively mitigate waste's environmental impacts beyond providing a financial surplus, thus avoiding the high costs of treatment and disposal.

In this context, this paper discusses the application of a novel material reusing organic waste from the agri-food industry, namely Spent Coffee Grounds (SCG) [23], generated as municipal organic waste from the process of espresso coffee brewing, aimed at addressing environmental issues and improving building energy performance in the villages of Madonie Park.

The scientific community's interest in reusing biomass waste in building and construction materials has grown significantly in recent years. This is due to the advantages of natural materials, such as low cost, lightweight, widespread availability, biodegradability, and their generally non-hazardous and renewable nature. Recently, these types of wastes have also been used in geopolymeric products, proving to be a promising inclusion in light of the circular economy approach and sustainability principles.

Previous studies conducted by Saeli et al. have also demonstrated the potential of reusing SCG for energy applications in construction [24,25]. Moreover, based on multicriteria methodologies, SCG have proven to be an optimal solution for advancing the building sector towards eco-friendly practices and have been effectively reused in traditional lime-based mortars to enhance the energy performance of building envelopes [26]. The performance of these novel bio composite materials was examined by incorporating various percentages of SCG into traditional hydraulic mortars with the aim of developing a high-energy plaster, namely thermoplaster, to be used as energy material for buildings' façade.

In this new work, the experimental SCG-based mortars were applied in a real residential building case study to showcase the effectiveness of the system already developed in previous studies. The main advantages are the low cost, lightweight nature, wide availability, and non-hazardous and renewable characteristics of natural materials, aligning with circular economy principles and sustainability goals. Moreover, the ease of manufacture and application in a real construction site is a plus for the effective technological transfer from the lab to the real world. All these provide socio-economic and environmental benefits associated with such interventions, including improved comfort for residents and reduced environmental impacts through waste recycling when applied in the construction sector, which promotes the principles of the circular economy [27].

2. Testing of the SCG-Based Mortars for Energetic Purposes

The laboratory SCG-based mortars showed a remarkable engineering performance suitable for high-energy construction applications, which, in this context, is intended to refer to applications where significant energy efficiency improvements are required. The processing and tests that were conducted also aligned with recent EU directives, and the thermal behavior proved to have effective energy performance [28]. Moreover, in accordance with ISO 20887 [29], the considered waste can be reused as non-reactive aggregate in the manufacture of novel materials and components, being stable, non-hazardous, non-volatile, and non-toxic, with 100% recyclability at the end of their useful life [30].

The building envelope is primarily responsible for the flow of heat from the external environment to the conditioned indoor spaces. Therefore, the thermal characteristics of construction materials used, along with technological design, play a crucial role in the overall energy performance of the building [29]. This necessitates specific design considerations tailored to each climatic condition and building requirement. The thermal transmittance of masonry walls in buildings represents the amount of heat that propagates from heated environments to colder ones through the wall's surface [31]. The key parameter for assessing thermal losses in a building is thermal transmittance, indicating the amount of heat crossing a specific surface when there is a one-degree Celsius temperature difference between the inner and external surfaces. Thermal transmittance plays a crucial role in the analysis of interventions aimed at reducing a building's energy consumption and ensuring optimal climatic comfort conditions. A lower thermal transmittance value corresponds to reduced thermal dispersion of the construction element and, consequently, improved thermal insulation. To determine the thermal transmittance value of composite elements, it is essential to rely on specific tools, such as software dedicated to thermal transmittance calculation [32]. These tools enable real-time thermal transmittance calculations and provide a graphical representation of temperature diagrams. During the design phase, they also allow the verification of compliance with thermal transmittance limit values established by minimum requirements decrees. The thermal transmittance of walls reflects the insulating capacity of the opaque structure, indicated by the thermal coefficient U, measured in W/m^2K [33]. The thermal transmittance value is crucial to understanding the effectiveness of the material used in building insulation, limiting thermal losses, and optimizing resources. It depends on the characteristics of the material constituting the structure, particularly the thermal conductivity (λ) and thickness. The UNI EN ISO 6946:2018 [34] provides the procedure to calculate the transmittance and thermal resistance of opaque elements, such as the walls [35]. Conversely, Thermal Resistance (R) represents the material's ability to resist the heat flow attempting to pass through it.

The energy performance of a building depends on the efficiency of its building envelope; if closure elements (vertical, horizontal, transparent, opaque) are not designed and constructed to meet the minimum requirements specified by current regulations, heat losses can exacerbate energy consumption and compromise climatic comfort. Once again, with energy certification software, it is possible to promptly determine the thermal transmittance of the building envelope, visualize the temperature diagram, and verify compliance with the thermal transmittance limit values set by the Minimum Requirements decree [36]. Additionally, an energy performance certificate can be obtained, and all legal checks can be carried out.

The thermal conductivity of SCG-based materials (λ) was measured using an HFM-CT 1000 calorimeter, following the standards outlined in UNE EN 12667:2002 [37]. To ensure accuracy, three tests were conducted for each formulation. Prior to testing, the specimens were meticulously dried at 60 °C for 24 h in a conventional oven. This drying process was essential to eliminate any internal moisture that could affect the measurement, as requested by the standard.

3. Case Study

The presented case study focused on the application of the developed thermoplasters in the context of the Polizzi Generosa municipality (Figure 1), one of the villages in Madonie Park, demonstrating its effectiveness in improving building energy performance [38] while preserving the architectural peculiarities of small Sicilian rural villages. This paper will present the technological feasibility of designing a coffee house using laboratory-developed bio-composite materials, promoting the building as an innovative, low-energy consumption architecture.

Figure 1. Madonie's basic historical traditional architecture.

Very few studies have focused on technological transfer, especially in the architectural area, making this study extremely innovative. Consequently, this work contributes to the development of alternative and technically valid yet extremely sustainable possibilities that can be effectively applied in the real-world building sector. This will facilitate an integrated architectural design process based on a customized and high-performance approach to design an innovative building envelope whose finishing layer is entirely composed of SCG-based plaster. This represents one of the first instances where a waste product is proposed and used as a material for energy-saving applications in architecture [26]. Virtual energy modeling has proven effective in a real-case building model using laboratory-developed SCG-based plasters [24], as also mandated by EU Regulation 2018/844 [39] on the energy performance of buildings. In this paper, the specific case study was a traditional building located in the village of Polizzi Generosa. Other studies were conducted on the village, for instance, to understand smart ways of improving and/or rehabilitating the local traditional stone masonry commonly affected by rising damp [40]. The examined building is situated in the historic center of the village and represents the recurrent type of traditional architecture that can be found in the Madonie territory [41]. Initially, the area of Polizzi Generosa and the surrounding conditions were analyzed to understand the relevant parameters of the study area, including climate, geographic data, and heating requirements. (Figure 2).

Metropolitan city	Palermo (PA), Sicily, Italy
Altitude	920 meters above sea level (m.a.s.l.)
Minimum	362 meters
Maximum	1869 meters
Geographic Coordinates	37° 48' 46.44" N 14° 0' 15.12" E
Seismic zone	2
Climatic zone	D
Degree days	2.037

Figure 2. Boundary conditions analysis of the Municipality of Polizzi Generosa.

The building was initially surveyed through on-site inspections. Subsequently, the measurements were accurately documented and implemented in energy assessment software. From an initial visual analysis, it was evident, especially in the facade, that the historical plaster exhibited various issues of durability, at times detached from the masonry and completely absent in certain areas [42]. More specifically, the considered building is a two-story masonry structure, finished with traditional lime-based plaster, extremely degraded, and a pitched roof covered in terracotta tiles. The considered building is also a row house, typical of Madonite construction, within a distinctive building complex that defines the examined area. The masonry consists of 50 cm-thick limestone blocks covered with a layer of traditional lime-based plaster, with an inner thickness of 2 cm and an external thickness of 3 cm. The roof is a single-pitched, wooden structure covered with Sicilian terracotta tiles. The inter-floor slab is made of a monolithic wooden structure. The building survey is presented in Figure 3.

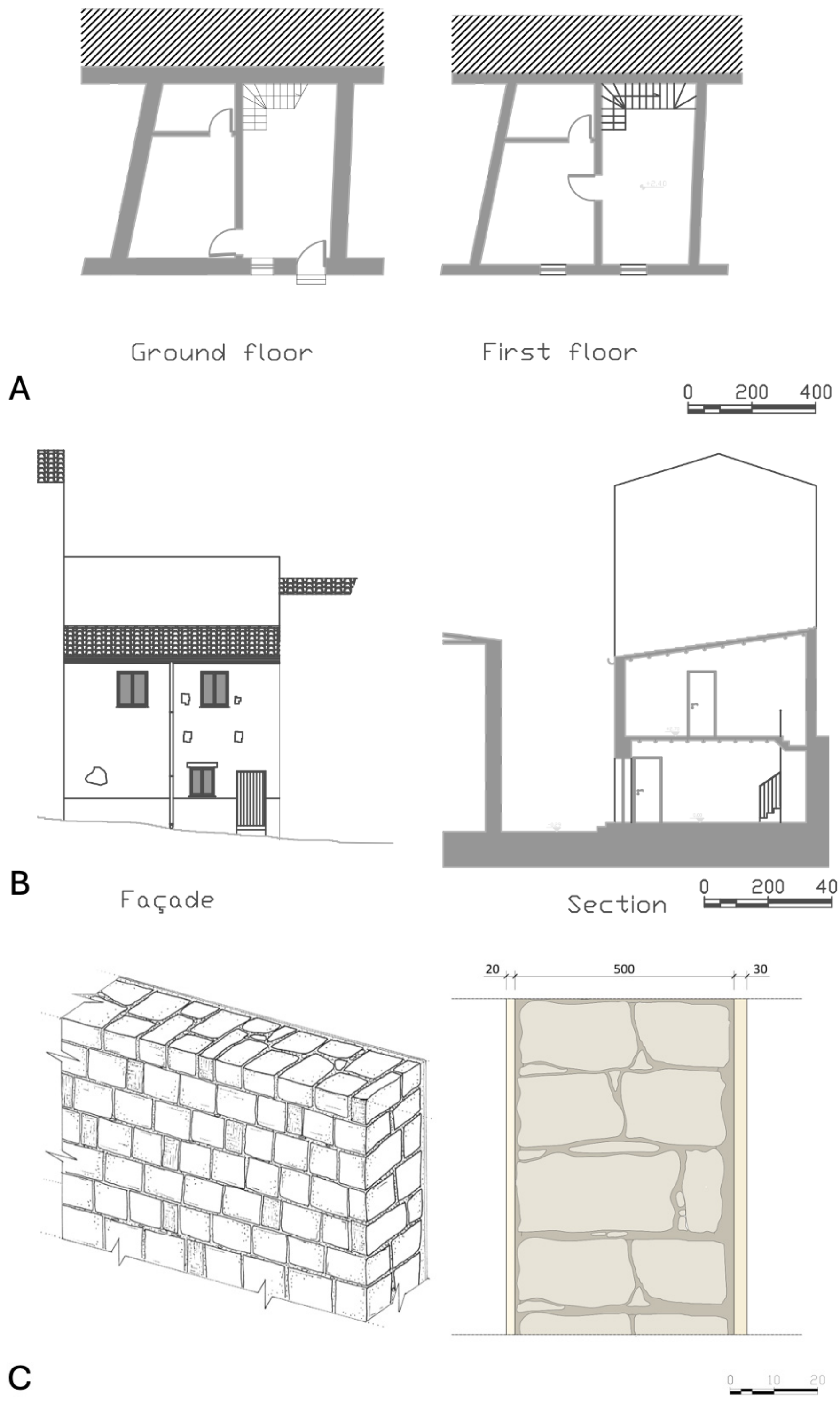

Figure 3. In-depth analysis of the studied building and section of the masonry wall stratigraphy (in detail: (**A**) Ground Floor and First floor plans. (**B**) Façade and Section. (**C**) Masonry and Stratigraphy).

4. Virtual Energy Simulation

4.1. Energy Simulation Software

The software used in this work to simulate the energy performance of the selected building in Polizzi Generosa is typically used in many Italian studies of architecture and engineering to calculate the technical elements of energy efficiency and verify a building's energy class [35]. These are Termus-G© (Version 42.00I) and Blumatica Energy© (Version 6.1) [43]. Hence, professional software was used in this work as local architects and engineers have shown many doubts about the possibility of developing realistic energy models that can use innovative, if not experimental, products for real applications. More specifically, Termus-G is a free-version energy-modeling software provided by the ACCA company (Bagnoli Irpino, Italy), which facilitates the calculation of thermal transmittance and assessment of interstitial condensation using the Glaser diagram [44]. This is crucial as it allows the understanding and monitoring of the stratigraphy's ability to maintain optimal values over a solar time span without potential gaps. One of the most commonly encountered issues in professional practice, through the use of these virtual programs, is the difficulty in utilizing unconventional materials that are not commercially available or cataloged within professional practice projects. For this reason, the analysis of the proposed thermal insulator values reported in the laboratory activity is critical, and their incorporation into the software being used is essential. The program follows an intuitive methodology to design wall or floor stratigraphy. By first entering the relevant municipality and assigning the Climatic Zone [45] (number D for the case study of Polizzi Generosa) through drag and drop directly from the archive, it was possible to select and position the desired masonry materials, graphically assigning their thickness and entering values for plasters, where necessary, from the database. Once the configuration was completed, the program automatically calculated the thermal transmittance of the surveyed wall. Results were visualized through a temperature diagram, providing immediate feedback on the thermal behavior of the structure. During the design phase, compliance with the thermal transmittance limit values set by the Minimum Requirements decree was also verified [46], according to the EU regulation [38,47]. Experimenting with thicknesses and types of available materials dynamically allowed the program to find the optimal solution to meet psychrometric and transmittance verification requirements, ensuring an efficient design aligned with regulatory standards.

The methodology adopted to verify interstitial and surface condensation of walls and floors also involved analyzing the amount of condensation and evaporation throughout the year. Using the Glaser Diagram, the software provided a detailed overview of relative and saturation pressure trends in different months. For each, values and diagrams of inner temperature, inner saturation pressure, inner relative pressure, inner relative humidity, external temperature, external saturation pressure, external relative pressure, and external relative humidity were provided. The hygrometric verification followed the specifications of UNI EN ISO 13788:2013 [43], ensuring a comprehensive and accurate assessment of the hygrothermal conditions in the environment throughout the year.

4.2. Methodology and Simulated Materials

Virtual energy simulation is the only methodology capable of reproducing the real behavior of a building system and understanding whether its real-world application on-site can result in an effective improvement in the thermal transmittance of the building envelope, both in terms of technological elements and overall, for the interior of the building. For this reason, the thermal transmittance of the wall section was fully analyzed. The initial phase focused on the analysis of (a) the as-it-is-built condition with traditional lime plaster (as can be typologically found in the Madonie area and used as a reference case); (b) the application of a commercial OPC-based plaster (a common product used in construction practice), and finally, (c) the best performing experimental SCG-based mortar (with 12.5 wt.% SCG), as fully described in [48]. The features of the energy material used are labeled in Table 1.

It is important to emphasize that, generally, the thermal conductivity of a wall built with squared limestone blocks shows a thermal conductivity value of 1.7 W/mK [49]. Typically, that value may vary depending on local materials and technological layers, such as plaster, which can either increase or decrease the transmittance.

Table 1. Energy features of the plasters used in the virtual simulations.

n.	Selected Type	Acronym	Thermal Conductivity (λ) [W/mK]	Vapour Permeability with Relative Humidity Up to 50% [GNs/kg]
1	Traditional lime plaster	TLP	0.900	8.500
2	Commercial plaster	CP	0.340	12.083
3	SCG-based plaster	SCGP	0.262	16.083

4.3. Thermal Analyses Implementation

Thermal analyses were conducted to assess the application of novel experimental thermoplasters in the traditional architecture of the Madonie area in contrast to traditional and commercial materials. In particular, the building used as a case study was directly modeled in Termus-G. Table 2 reports the stratigraphy of the walls used.

Table 2. Virtual model technological features.

Case n.	External Plaster		Local Limestone Masonry	Inner Plaster		Plaster Surface Mass [kg/m^2]	
	Type	Thickness [mm]		Type	Thickness [mm]	External	Inner
1	TLP	30	50 cm thick, λ = 0.550 W/mK	TLP	20	54	36
2	CP			CP		42	28
3	SCGP			SCGP		42	42

Subsequently, the selected/simulated plasters were applied to the case study, and the masonry energy simulations were run considering the dynamic thermal power exchanged between two environments, each operating at temperatures T_{inner} = 20 °C and $T_{external}$ = −2 °C. Figure 4 shows the thermal analyses of the three analyzed cases. Table 3 reports the obtained values.

Table 3. Resulting transmittance of the masonry cases modeled.

Case n.	Masonry Transmittance (U) [W/m^{2}K]	Δ U (TLP Trasmittance—CP and NPC Masonry Transmittance)	Reduction %
1	0.881	0	-
2	0.816	0.065	7
3	0.788	0.093	11

The conducted thermal simulations revealed that the transmittance values for the three cases were TLP—0.881 W/m^{2}K, CP—0.816 W/m^{2}K, and SCGP—0.788 W/m^{2}K. It is interesting to note that the typical commercial plastering system reduced the transmittance by approximately 7% compared to traditional plaster, while the experimental one by up to 11%, ensuring a lower final transmittance over the large surface area of the wall.

To verify this claim, an energy class analysis of the building was also conducted, considering its daily use and replacing the traditional plaster (TLP) with the experimental (SCGP) one. In this case, a highly diffuse professional software, Blumatica Software, was implemented. This software is widely used in professional practice to assist technicians. The results in Figure 5 demonstrated a reduction in the building's energy consumption and, consequently, a decrease in the management costs of the studied building.

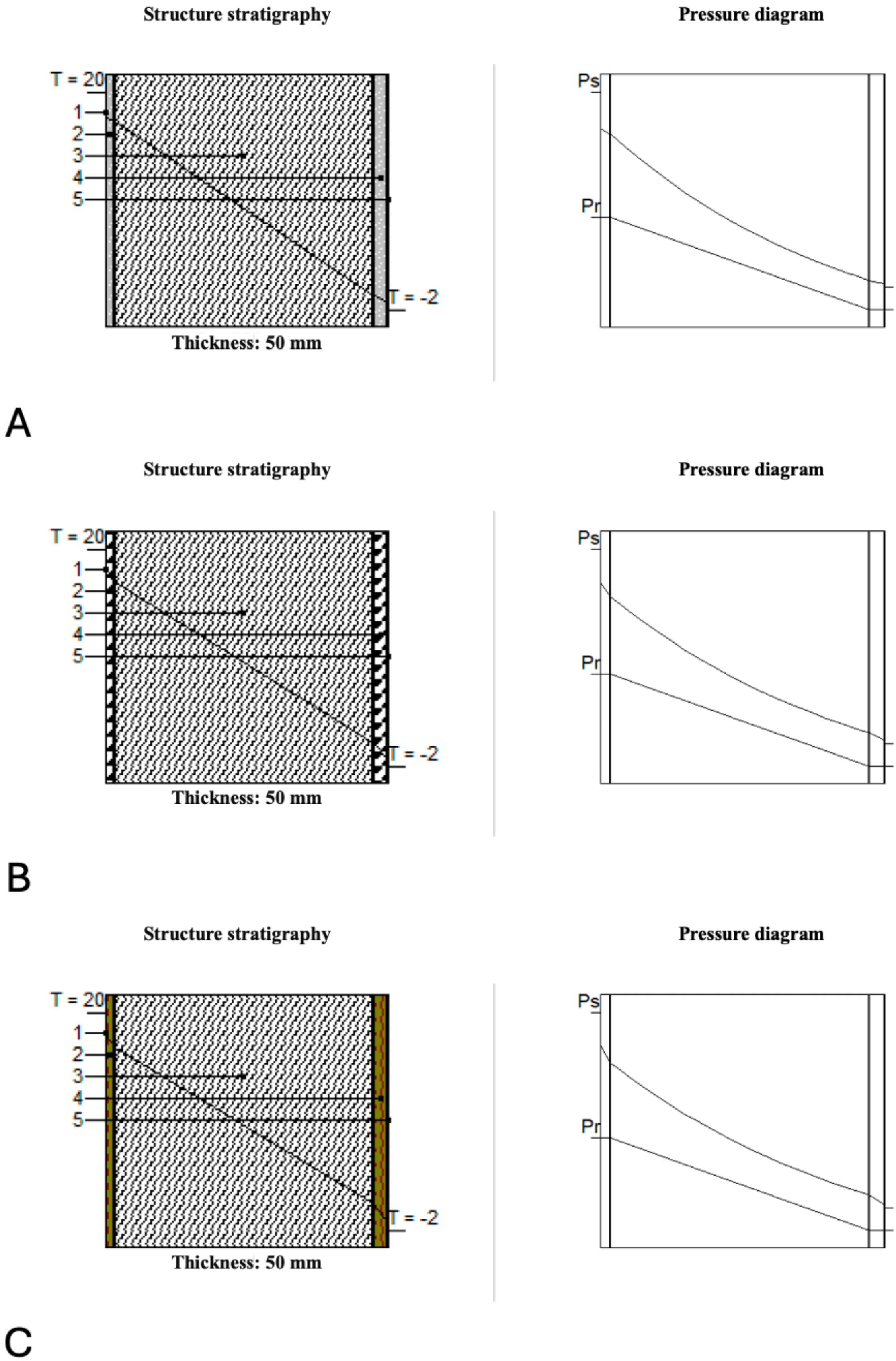

Figure 4. Thermal analysis of the examined cases. (**A**) Case n.1 TPL, (**B**) Case n.2 CP, (**C**) Case n.3 SCGP.

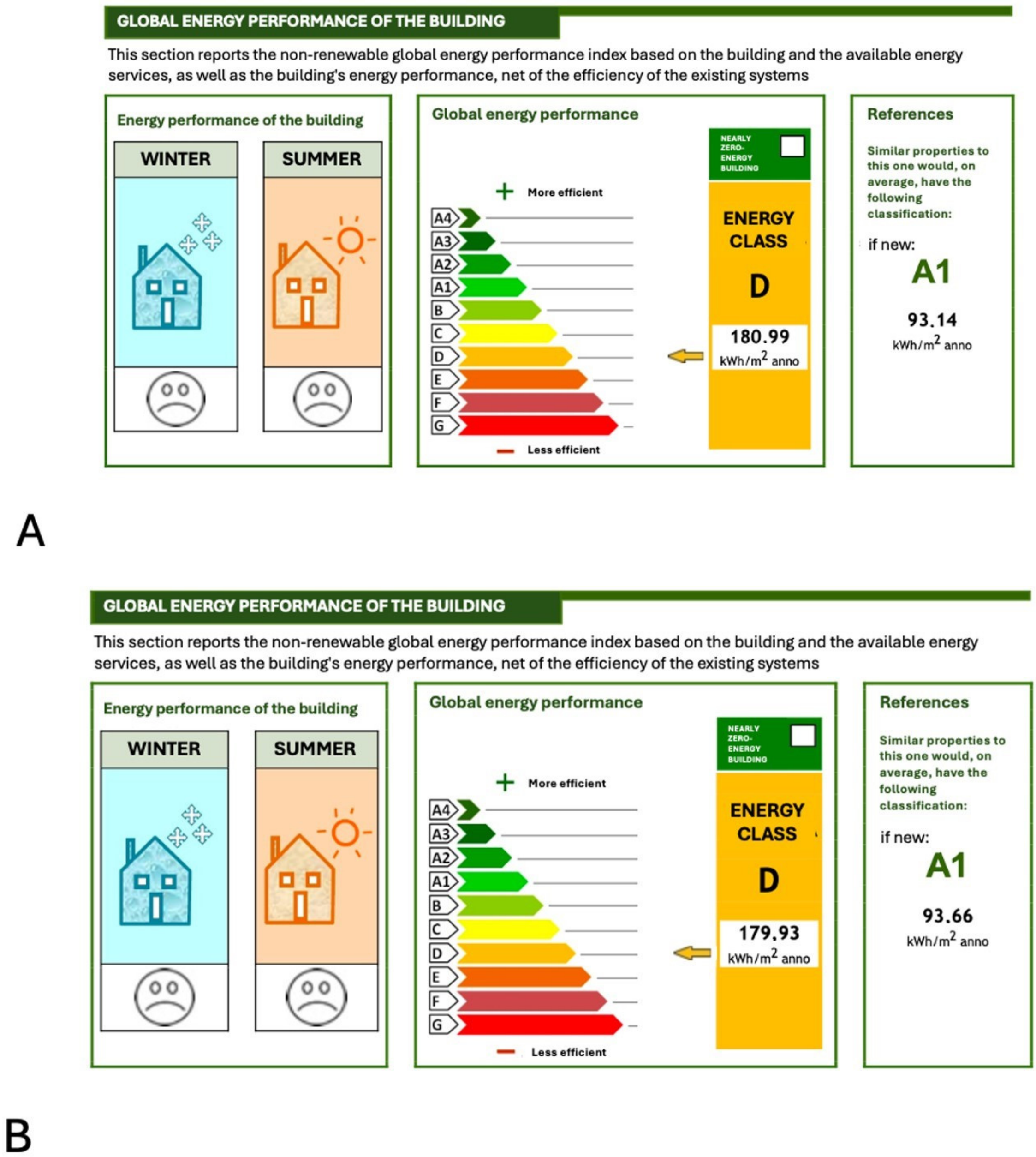

Figure 5. Results of the building's energy simulation before (**A**) and after the application of the experimental plaster (**B**), according to the European Regulation: Directive 2010/31/EU of the European Parliament of 19 May 2010 on the energy performance of buildings and UNI/TS 11300-1:2014 [43].

Moreover, it is important to observe that, from the conducted analysis, condensation does not occur in any of the three cases. This indicates that all three plasters used did not create problems for the wall, which remained in excellent condition in all instances. However, February was identified as the coldest month, during which the curves were very close but did not intersect, thus not causing significant damage. From these data, it is evident that all three masonry transmittance values were exceptionally low, each being below 1; however, the lowest value was recorded with the application of SCGP, which is the experimental one.

This result not only highlights that the use of bio composites can be advantageous in reducing plaster transmittance values, but it also suggests that the application of such materials could promote sustainable construction. Although traditional building techniques were used, innovative materials were incorporated through the utilization of waste and the promotion of the recovery and reuse of unconventional resources, such as spent coffee grounds (SCG). Therefore, even at the end of its life cycle, coffee—or rather its waste—can be employed in the construction sector, thus contributing to a more sustainable management of resources and a reduction in environmental impact.

5. Making "Smart" Inner Villages by the Smart Use of Innovative Materials

The analysis conducted through the Termus-G software revealed three distinct outcomes. Specifically, it was evident that, compared to traditional lime plaster, the two selected plasters—commercial (CP) and experimental (SCGP)—applied to the wall showed superior energy performance. In particular, the experimental SCGP allowed for lower wall transmittance, ensuring a greater improvement in indoor comfort. From a scientific standpoint, the SCGP showed a higher thermal efficiency compared to traditional finishing, thanks to the insulating properties of the waste components. This characteristic could positively impact the wall's ability to manage thermal flow, thereby contributing to better thermal regulation of the indoor spaces and overall improved living comfort.

Further analyses conducted using the Blumatica Energy software (6.1 version) allowed for the assessment of the building's behavior in its current state and after the implementation with the SCGP. Blumatica Energy is a specialized software designed to support various functions in the fields of energy efficiency and construction. It is tailored for the compilation of Energy Performance Certificates (EPC) and the assessment of Building Environmental Quality (BEQ) in accordance with Italian regulations, including Law 10. The software facilitates the creation of detailed technical reports and calculations required for energy certification of buildings. Blumatica Energy provides advanced tools for calculating thermal transmittance values and conducting thermo-hygrometric verifications, offering precise evaluations of building thermal performance. It includes feasibility studies for energy improvement interventions and supports regional data export capabilities. Using 3D building modeling, the software enables detailed energy simulations to understand the thermal behavior of building components. It allows assessment of the building energy class during design, construction, and post-implementation of new technological and HVAC solutions, enabling better control and optimization of building energy performance.

The simulations demonstrated that, in comparison to the initial energy class D, there was no significant variation in energy class. However, there was an improvement in the overall building's energy consumption by approximately 1 kWh/m^2 per year. When combined with other sustainable technological solutions, such an apparently low increase could contribute to achieving a high-performance building with a higher energy class and lower energy consumption.

Indeed, the concept of a SMART village, pursued by this research, aims to find long-term, innovative, and sustainable solutions for the construction sector, particularly in small mountain communities, with a specific focus on Madonie Park and its 21 municipalities. The implementation of a strategy that combines tradition and innovation, using an experimental and innovative waste-based plaster with very low thermal transmittance, further supports the idea that adopting an advanced technological strategy, beyond being in line with the circular economy approach, can inevitably lead to an improvement in the thermal performance of an outdated and technologically lacking building sector.

Integrating tradition and innovation is a complex challenge, but the use of innovative materials with the involvement of academia and research demonstrates that innovation in well-preserved contexts is still possible, contributing to improved comfort and, inevitably, promoting urbanization in remote areas. This highlights that improving heritage buildings can, in turn, contribute to the enhancement of inner areas. Furthermore, the possibility of recovering and reusing waste, in line with the goals of the 2030 Agenda [50], paves the way for a more sustainable future.

In this way, anyone choosing to live in the Madonie region will have access to healthy, durable, and competitive buildings compared to new constructions in large cities without sacrificing the charm of living in mountain villages surrounded by lush nature. This embodies the essence of the "smart village" precisely. The current research focused on analyzing building performance. It could, if developed further, improve other technical aspects of construction and allow for additional technological, social, or environmental implementation. According to recent research, the route shown here could even lead to buildings with a very low energy class, approaching the concept of a nearly zero-energy building (nZeb) [51].

It is evident that, within the context of nearly zero-energy buildings (nZeb), the exclusive use of thermal plaster is insufficient to achieve a high energy performance rating. Indeed, a layer of just 3 cm of plaster alone cannot provide adequate thermal insulation to achieve high-level energy performance. However, it is crucial to consider that the overall energy performance of a building does not depend solely on the building envelope. It is the combined result of various factors, including the installed technological systems. These systems, as accounted for by the design software, are automatically included in the calculations and significantly contribute to achieving the desired energy performance. Therefore, the final assessment of an nZeb building's energy rating must take into account both the characteristics of the building envelope and the efficiency of the integrated systems.

This strategy could also be applied in similar contexts to promote "Smart Coffee-House" in other similar contexts, spreading an innovative building practice that includes a robust strategy for smart recovery, smart rehabilitation, and smart enhancement of existing heritage.

6. Conclusions

The analyses showed that SCG could be efficiently used to manufacture innovative and highly eco-sustainable thermoplasters to improve the energy efficiency of buildings. Furthermore, the final performance of the analyzed case study, a traditional building of the Madonie area, demonstrated not only a reduction in the transmittance of the building envelope but also an encouraging decrease in overall energy consumption. The developed material meets the technological standards while simultaneously reducing the associated environmental footprint and costs. Additionally, the use of a significant amount of raw waste aligns with the European directives on the Minimum Environmental Criteria [52]. A new methodology for the disposal of biological waste has also been proposed as an alternative to landfill and its consequent environmental issues. The conceived technological solution also justified a compatible recovery of the heritage building, oriented toward energy efficiency, and can be widely applied in all areas of the Madonie mountains or other worldwide locations characterized by similar climatic data and construction materials.

Similarly, with the same care that this research has shown and using the same methodology, novel experimental bio-composites could find appropriate applications in construction based on their engineering performance [53]. Some mixtures could be suitable for low thermal transmittance masonry in construction and/or repairs. Their excellent thermal and energy performance makes them suitable for practical application, even surpassing conventional materials, and highly effective for energy applications in architecture. Based on that, the relevant conclusions are as follows:

Circular economy approach and sustainability: The high rate of reused waste (SCG) helps reduce landfill disposal and its associated environmental pollution, improves the local economy by providing an additional financial surplus for waste producers and municipalities and reduces the carbon footprint through greener production processes;

Scalability: The methodology and materials used are designed to be scalable, allowing for widespread application across various sizes and types of projects. This scalability ensures that the benefits of using SCG and similar waste materials can be replicated in different settings, ranging from small- to large-scale developments, thereby amplifying the positive environmental and economic impacts;

Technological Transfer: This process facilitates the transfer of technology and knowledge to professional firms, enabling them to simulate and apply innovative and highly competitive materials in their projects. By using the same methodology, these firms can explore new

materials and techniques that rival those available in the commercial sector. Stakeholders, including industry professionals, were actively consulted to identify challenges and provide support in the practical application of these materials. This collaborative effort reflects the strong commitment of professionals to advancing their field and integrating cutting-edge solutions;
Adherence to the EU regulation: The project aligns with European Union regulations concerning environmental sustainability and energy efficiency. Compliance with these standards ensures that the materials and methods used not only meet regulatory requirements but also contribute to the EU's broader goals of reducing carbon emissions and promoting sustainable building practices;
Reduction in energy consumption: Utilizing a higher quantity of SCG in building materials contributes to a reduction in overall product costs. Additionally, the incorporation of waste-based materials can enhance the thermal performance of buildings, leading to lower energy consumption for heating and cooling and further supporting environmental and economic sustainability; Cost: A higher quantity of SCG reduces the product cost;
Complete building envelope: The compatible recovery of the heritage building through the use of waste-based materials demonstrates how a similar large-scale application could contribute to the development of smart communities, promoting the energy efficiency of the building sector and transforming these communities into intelligent and technologically innovative residential complexes.

Further investigations will consider the possibility of integrating different types of waste into the building envelope to achieve greater material sustainability and superior energy performance. Energy simulations will be conducted to understand the potential technological limits of the proposed application, and more accurate simulations will be performed across a wide range of climates and architectural and technological solutions to better correlate the amount of used waste and energy improvement across various latitudes. Finally, the possibility of obtaining certification (e.g., ReMADE, LEED, or GBC) based on consistently reliable results will be considered along with real-world application of the studied materials.

Author Contributions: M.S. was in charge of novel materials development, engineering characterization, and building applications; L.L. conducted the thermal analyses on the building case of study; T.C. was in charge of the scientific coordination. All the authors were involved in the manuscript preparation and implementation. All authors have read and agreed to the published version of the manuscript.

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