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Comparative Study of Natural Fibres to Improve Insulation in Wooden Beehives Using Sensor Networks

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Abstract: The beekeeping sector is increasingly focused on creating optimal and natural environments for honeybees to reduce dependence on external factors, especially given progressively hotter summers. Improving hive thermal conditions can enhance bee wellbeing and production. While pinewood hives are predominant, some have started using insulating materials like polystyrene. However, many synthetic materials, despite their excellent insulation properties, are incompatible with organic food production, requiring alternative solutions. This study compares the thermal insulation properties of various natural materials, including white and black agglomerated cork, wood fibres, and rock mineral wool. These materials are potentially compatible with organic food production. Additionally, the research evaluates cost-effective sensor networks to monitor bioclimatic variables in real time. Lab tests using a Langstroth-type hive with a controlled heat source were conducted, monitoring temperature and humidity inside and outside the hive. The results revealed that all selected materials provided similar thermal insulation, superior to a hive without insulation. This finding suggests that using natural materials can enhance hive thermal comfort (i.e., the material's ability to maintain a stable internal temperature), thereby improving honeybee wellbeing and productivity in a manner compatible with organic food production.

Keywords: thermal insulation; bees; beekeeping; natural origin insulators; digitalisation

Citation: Sanz, M.C.; Prado-Jimeno, R.; Fuentes-Pérez, J.F. Comparative Study of Natural Fibres to Improve Insulation in Wooden Beehives Using Sensor Networks. *Appl. Sci.* **2024**, *14*, 5760. https://doi.org/10.3390/app14135760

Academic Editor: Roberto Romaniello

Received: 27 May 2024
Revised: 18 June 2024
Accepted: 25 June 2024
Published: 1 July 2024

1. Introduction

The honey bee (*Apis mellifera* Linnaeus, 1758) is one of the most important organisms of the world due to its contribution to 75% of the pollination of vegetable crops, 35% of which depend directly on this mechanism, along with other pollinators [1]. The monetary value of this ecosystem service has been estimated at 351 billion $ (USD) per year [2]. In addition, 90% of wild plants have generalist animal pollination strategies [3]; therefore, the honeybee directly contributes to maintaining the biodiversity of flora. However, the honey bee is also one of the species most impacted by global change, being seriously affected by harmful agrochemicals [4] and the appearance of invasive species such as *Varroa destructor* Anderson and Trueman, 2000 [5] or *Vespa velutina* Lepeletier, 1836 [6], and global warming [7–11], among other factors.

The development of the beekeeping sector has standardised the internal dimensions of the hives to a regular frame size and are mainly made of softwoods, pine, and spruce in the majority [12,13]. The most common beehives have movable frames [14], and there are several variants, such as Langstroth, Dadant, and Layens, depending on their dimensions and/or the position of their modules. The Langstroth hive, created in 1852, is the most widely used [15]. Wood has established itself as the most commonly used material for beekeeping due to its good mechanical properties, stability, ease of mechanisation, affordability, and satisfactory insulation properties. However, there are additional organic materials, such as cork or wood fibre panels, that could offer superior insulation properties.

In recent decades, hives made of synthetic materials such as polystyrene and polyurethane have been developed and tested, yielding better results in cold climates [16–18]. However, the use of these synthetic materials is not always satisfactory due to their fragility and excessive impermeability and because they cannot be used for organic production due to European legislation. In contrast, conventional wooden hives do not exhibit these drawbacks.

Historically, the construction of hives has been influenced by the availability of suitable materials, as noted by [19]. These materials ranged from terrestrial ones, such as sun-dried mud and baked clay, to plant-based materials, like hollow logs, cork bark, woven cylinders, splint stems, and wooden boards. In Mediterranean areas, cork bark cylinders were commonly used. Known for its superior insulating properties compared to wood, cork has traditionally played a significant role in hive construction.

Although cork was one of the first materials used to make hives along with baked clay, wicker, or hollow logs [20], few publications are found with hives exploiting the incorporation of such natural fibre insulations in modem designs. Floris et al. [16] analysed wooden hives with anagglomerated cork through field work in Sardinia (Italy) and evaluated the interior temperature thermoregulation of wooden hives and hives incorporating 3 cm of this natural fibre inside, achieving a more regular daily temperature pattern. Whereas there are research works that have analysed the interior temperature of the hive comparing wooden and plastic hives in field trials [16–18], there are hardly any results and investigations of standardised laboratory trials incorporating and comparing different natural fibres. Regarding polystyrene hives, they present higher thermal insulation compared to conventional ones but with significant disadvantages in relation to their higher price [21], lower durability [22], lower sustainability [12] and their prohibition for organic production [23]. Additionally, hives that are overly insulated from the external environment may encounter issues with internal overheating, which cannot always be efficiently mitigated by the bees' natural regulatory behaviours [24]. Research has also been carried out on the development of new materials, such as ferrocement [25], cement-vermiculite mortar [26,27], or reinforced clay [28].

Considering all these, the objective of this study is to conduct a comparative laboratory analysis of natural insulating materials in a Langstroth-type hive subject to a controlled heat source. The study compares the evolution of humidity and temperature through sensors both inside and outside hives. Furthermore, capitalising on this opportunity, we also aim to test a new sensing network based on open technology. This network will monitor internal and external environmental variables in hives, offering precision and affordability in contrast to available alternatives such as the World Bee Project CIC (WBP), the Slovakian project Bee Hive Monitoring from 2022, and various companies that sell sensors ready for hive integration, including BuzzBox (Denver, CO, USA) and Hive Watch (Tann, Switzerland), among others. The developed network takes into account the unique circumstances of the beekeeping sector in the Iberian Peninsula, specifically the lack of reliable communications due to the region's terrain, the ageing demographic of the sector, and the prevalence of digital immigrants. The results from the study suggest that it is indeed possible to improve the insulation of hives and monitor them in real time to track the daily cycle within each hive. Therefore, these findings will directly contribute to the conservation and adaptive management of hives in the field. This would have direct implications for the survival of bees, potential increase in production, and reduction in costs stemming from unnecessary management actions.

2. Materials and Methods

2.1. Tested Materials

The beehive model used was the Langstroth [29]. Designed by Lorenzo Lorraine Langstroth in 1851, the Langstroth beehive is one of the most popular beehive designs globally. It offers several advantages over other hive types, including a design based on the bee space principle, modularity, efficiency in honey harvesting, standardisation, ease of inspection, maximised honey production, adaptability, longevity, and durability.

The selection of materials for this study was guided by a multicriteria approach that prioritised ecological sustainability, regional availability, and safety. We focused on natural materials that offered a viable alternative to synthetic insulators, specifically targeting those with a reduced environmental impact. This selection process ensured that our study utilised materials that were not only environmentally friendly but also locally accessible and safe for intended applications. Given these considerations, four different insulating materials with specific thermal conductivity coefficients were chosen, all of which have a natural origin: black agglomerated cork, white agglomerated cork, wood fibres, and rock mineral wool. Black agglomerated cork is produced by using the cork's own natural resin, suberin, as a binder for the cork particles. This process not only enhances the material's insulating properties but also maintains its ecological integrity. In contrast, white agglomerated cork, also known as composite agglomerate, incorporates synthetic resins as binders. This difference in manufacturing can significantly affect its thermal and physical properties. The characteristics of these materials are presented in Table 1.

Table 1. Characteristics of the insulating materials tested.

Material	Thickness (mm)	Density (kg/m^3)	Thermal Conductivity ($W/(m\cdot k)$)	Reference
Wood fibre band STEICO Roundtrip	8	60	0.038	[30]
White agglomerated cork	10	200–220	0.045	[31]
Black agglomerated cork	13	100–120	0.036–0.038	[32]
Ultracoustic R rock mineral wool	8	32	0.032	[33]

2.2. Experimental Procedure

Experiments were conducted in a controlled environment using a custom-built chamber equipped with a controllable heat source (two infrared lights of 250 W), as depicted in Figure 1. Each hive, outfitted with each type of insulation described inside its side walls and under its cover, along with a control hive without insulation (total 6 hives), were placed inside this chamber and subsequently exposed to a heating cycle (target temperature 60 °C; experiment duration 3 h). To ensure the robustness of our materials under extreme conditions, we conducted tests at a temperature of 60 °C, which is notably higher than any temperature recorded at our study site according to our collected field data. This temperature was chosen to simulate extreme stress conditions that might not typically occur but are critical for assessing the safety and effectiveness of the insulation materials under potential future climate variations. Also, the melting temperature of the wax is nearly 60–65 °C [34,35]. Despite the experimental duration being 3 h, the final analysis consisted of only 1 h to achieve a common starting temperature between different materials (see Section 2.4). Between each experiment, a waiting period was established until the chamber returned to the outside temperature. The chamber's temperature was regulated by a compact temperature control system composed of an M0 microcontroller board, a digital thermometer, and a set of relays to control the heat source. This system maintained the chamber's temperature with an accuracy of ±1 °C from the target temperature. Additionally, a fan system was employed to ensure uniform temperature distribution. The changes in temperature and humidity within the hive and the chamber were monitored every 30 s using the developed sensor network (refer to Section 2.3). Each insulation material was tested in three replicate experiments (total 6 × 3 = 18 experiments).

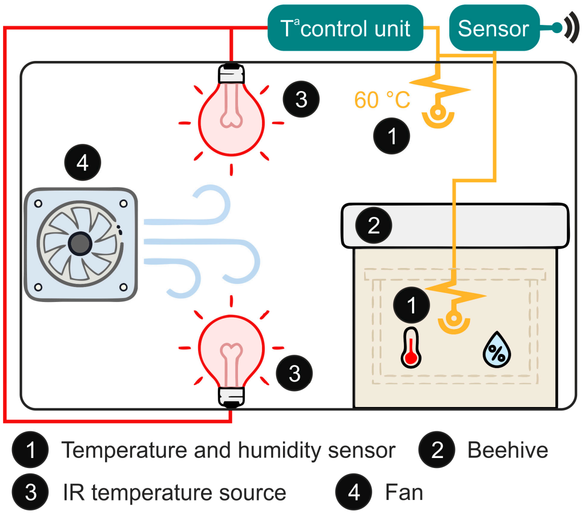

Figure 1. Sketch of the box where the tests were carried out with the lamps and the humidity and temperature sensors in the exterior and interior of the hive.

To further bolster the validity of our experimental results, a supplementary test was carried out. While the primary intent behind this second experiment was not to draw new conclusions, it aimed to provide additional support for our findings. We selected one of the materials to study the heat dissipation behaviour, comparing a control hive (without insulation) and a hive insulated with a black agglomerated cork. This comparison was visualised using a thermal camera. Both hives were equipped with a 250 W infrared lamp and humidity and temperature sensors, positioned identically, as shown in Figure 2. Measurements began with the ambient temperature and continued throughout a heating period of 30 min. Once the lamp was turned off, we kept recording data during the hives' 30 min cooling phase.

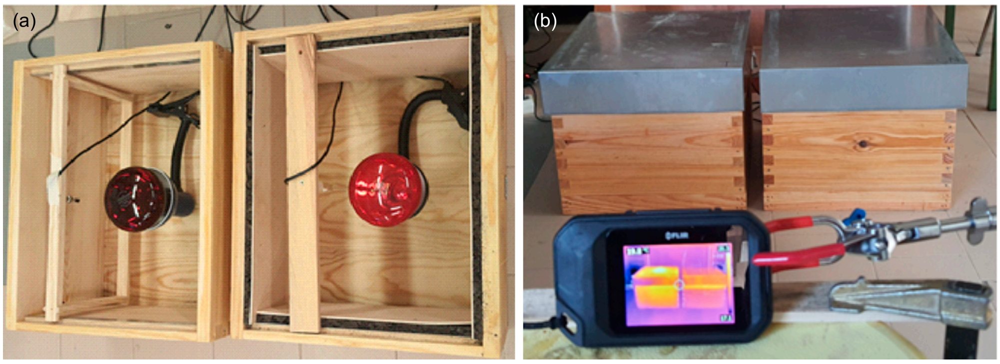

Figure 2. (**a**) Inside view of the hives featuring lamps and sensors: on the left is the control hive, and on the right is the hive insulated with black agglomerated cork. (**b**) Thermal camera monitoring.

2.3. Sensor Network

2.3.1. Hardware

One of the objectives of this work was to implement and test a sensor network for remote hive monitoring. For this purpose, a custom sensor node (Figure 3) was developed to monitor humidity and temperature inside the beehives, as well as external environmental variables (pressure, temperature, and humidity). The sensor's main processing unit is the MC Sentinel V1.1, a microcontroller board designed by the University of Valladolid for rapid IoT prototyping. This board integrates, in a compact form factor, an ESP32 microcontroller, an RTC (DS3231), an SD card holder (to store the data), and an autopower circuit [36]. Additionally, the node features a custom PCB integrating a LoRa radio module [37] and a

186,500 lithium battery holder (battery duration 1 year at 15 min transmission interval) and provides easy-plugging contacts for quick sensor attachment. While the developed node can accommodate various sensors and alternatives, an SHT31 [38] was used for internal beehive monitoring, and an AHT20 [39] and a BMP280 [40] were used for external variable measurement.

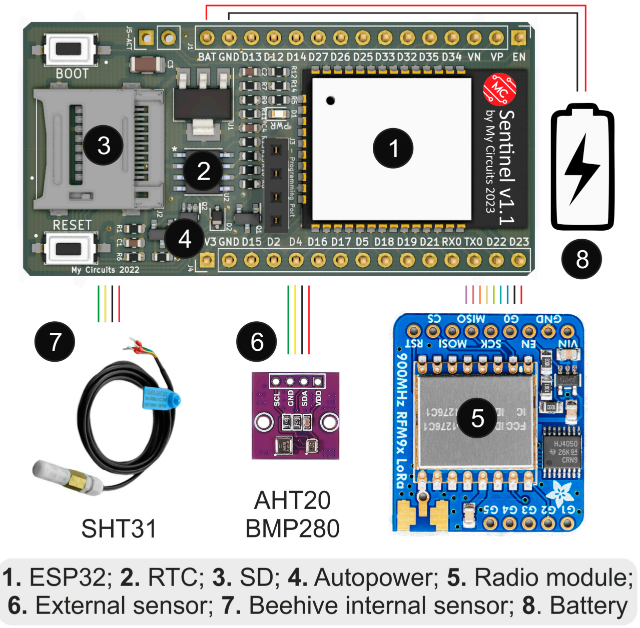

Figure 3. Architecture of the nodes implemented for remote monitoring of beehives and main components. The node supports a wide range of sensors.

The node can store data independently while also transmitting it via radio. To visualise and store these data in real time online, we developed a gateway. The straightforward yet effective gateway used for the experiments comprises a commercial ESP32 board linked to a LoRa radio module. This setup both prints the collected data via a serial connection and sends it to an online server. Another architecture that we implemented and tested, as cited in [41], is designed for more challenging conditions. It consists of a small single-board computer, the Raspberry Pi 4, connected to an Atmel ATSAMD21G18 microcontroller with an integrated LoRa RFM95 radio module and a 4G modem.

2.3.2. Software

The node and the gateway are programmed in C using the Arduino Integrated Development Environment (IDE). The code facilitates encrypted communication between nodes and the gateway. Each node possesses a unique address, enabling the gateway to identify each one and synchronise their transmissions.

In the developed workflow, the gateway anticipates the data transmission from the node. Subsequently, the node gathers sensor information, saves it to the SD card, and relays this information to the gateway. If the transmission is successful, the gateway communicates a new wake-up time to the node. The node then sets a new wake-up alarm and powers down.

This process aims to (1) conserve power in the nodes by shutting them off, (2) synchronise data transmissions, and (3) allow the gateway to control the sampling rate. If a specific node fails to respond, the gateway recursively attempts communication for a set number of cycles (defaulted to 2). If subsequent communication efforts remain unsuccessful, the gateway initiates a management alarm and proceeds with other nodes (Figure 4). Once the gateway collects a sample from each node, it stores the data locally and also on an online server (using HTTPS queries + MySQL 8.0.36) for long-term assessment (Figure 4). The developed architecture supports the integration of alarms in the gateway through the programming of data assessment scripts or specific algorithms. However, this was outside the scope of our study and is reserved for future field deployment of the network.

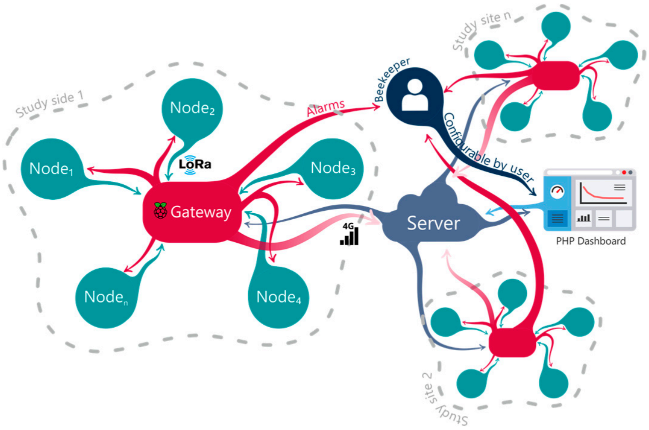

Figure 4. Communication architecture of the field sensor network.

2.4. Data Treatment and Validation

Each hive insulation test was conducted three times, during which both internal and external temperatures, as well as humidity, were continuously monitored. To ensure consistency and facilitate cross-experiment comparisons, a standard starting temperature of 22 °C inside each beehive was established. From this set point, thermal activity within the beehive was calculated based on the area under the temperature curve from the moment 22 °C was achieved until one hour later. This method was uniformly applied across all replicates to evaluate the thermal insulation efficiencies of the different materials. The maximum temperature reached within this period was also recorded for each type of insulation.

Data were collected and stored as separate text files for each test. Initial graphical assessments of these files helped pinpoint the commencement of the experiment when the target temperature in the chamber was met. The primary metric for comparison was temperature, considering no humidity control mechanisms were implemented during the experiments. However, humidity data were recorded and may be pertinent for future studies or specific applications.

Statistical analysis was performed using R version 4.2.0 [42] and Statgraphics Centurion XVIII. We employed ANOVA to determine significant differences between the insulation materials' performance, ensuring robust comparative analysis. This method was specifically chosen for its ability to handle variance within and across groups, which is ideal for our experimental design. Following the identification of significant effects via ANOVA, Fisher's least significant difference (LSD) test was utilised as a post hoc analysis to further explore pairwise differences between group means.

Regarding data integrity, any outliers identified during the initial graphical assessment were scrutinised to ascertain whether they resulted from experimental errors or genuine anomalies. Since the experimental conditions were highly controlled, significant deviations were rare. In the absence of outliers, no data points were excluded from the analysis. Had there been missing data, imputation techniques would have been employed to maintain data completeness, ensuring no loss in data reliability. Thankfully, our data collection process was meticulous, resulting in a complete dataset without any missing values. Through these procedures, we ensured the reliability and accuracy of our findings.

3. Results

3.1. External Heating Source

The raw results of external insulation laboratory tests for each insulating material are shown in Figure 5. The evolution of the different monitored variables is similar among all materials. The graph illustrates the evolution of temperature and humidity both inside and outside (i.e., in the chamber) of the hive over the test period. In all cases, the external temperature rises rapidly, while the interior temperature of the hive increases more gradually, demonstrating the insulating properties of the hives. Similarly, external humidity decreases quickly due to the absence of a humidity control system, allowing humidity to escape the chamber easily. Inside the hive, the humidity initially increases because of limited air exchange with the chamber but eventually begins to decrease as the interior air starts to exchange more actively with the chamber.

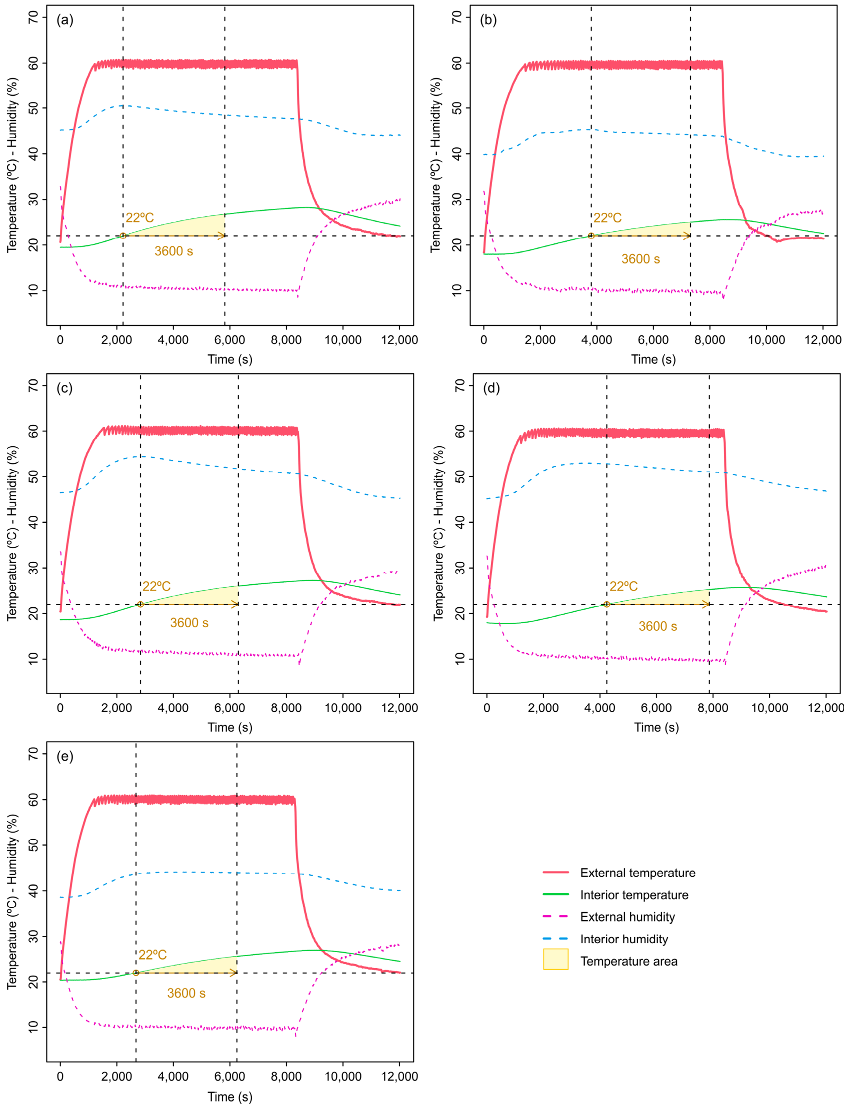

Figure 5. Graphical representation of the indoor and outdoor temperature and humidity variables obtained in the laboratory test for (**a**) control hive, (**b**) rock mineral wool hive, (**c**) wood fibre hive, (**d**) black agglomerated cork hive, and (**e**) white agglomerated cork hive. The yellow area has been calculated at 22 °C indoors and for a time of 1 h to compare the insulating capacity of each material.

The overall cumulative temperature area for all materials is smaller than that of the control experiment. However, it should be noted that for comparison purposes, the commercially available materials employed had varying thicknesses, so normalisation was crucial. Similarly, due to external factors like the starting temperature outside the chamber, it is essential to begin comparing materials at a consistent temperature (22 °C). This requirement results in different starting times for each experiment.

The results are consistent across experiments and materials (Online Resource 1), with no significant differences between replicates. Considering this, the integration of variables among materials, along with descriptive statistics and an analysis of variance for the variables "area/thickness" and "maximum temperature after 1 h of exposure at 60 °C", are shown in Table 2.

Table 2. Descriptive statistics and ANOVA results for the variables: area/thickness and interior temperature after 1 h at 60 °C (* *p*-value < 0.05). Last column summarises the pairwise comparison after Fisher LSD. "a", "b", and "c" represent the groups within the pairwise comparison.

Variable	Material	Average	Standard Deviation	Coefficient of Variation (%)	*p*-Value	Pairwise Comparison
Area/thickness	White agglomerated cork	234.547	27.675	11.799	0.0000 *	ab
	Black agglomerated cork	188.473	16.23	8.615		a
	Rock mineral wool	255.197	4.709	1.845		ab
	Wood fibres	218.227	32.12	14.719		b
	Control	418.137	38.174	9.129		c
Indoor temperature after 1 h at 60 °C (°C)	White agglomerated cork	26.14	0.470	1.799	0.0071 *	a
	Black agglomerated cork	25.57	0.278	1.090		a
	Rock mineral wool	26.093	0.090	0.347		a
	Wood fibres	25.563	0.524	2.053		a
	Control	26.967	0.402	1.493		b

The control hive has a significantly larger temperature area and a higher area/thickness ratio compared to the other hives. This observation is also mirrored in the maximum temperatures recorded: the control hive reached 27 °C, while hives with natural fibres displayed reduced temperatures, 26.1 °C for white agglomerated cork and wood fibres, and 25.6 °C for black agglomerated cork and rock mineral wool.

In terms of thermal insulation, specifically referring to the maximum internal temperature after 1 h with an external temperature of 60 °C, the comparative ANOVA analysis results (presented in Table 2) show no significant differences between the four selected materials: black agglomerated cork, white agglomerated cork, wood fibres, and rock mineral wool, as illustrated in Figure 6b. Any of the selected insulators offers significant differences in performance when compared to the control hive, which lacks insulation.

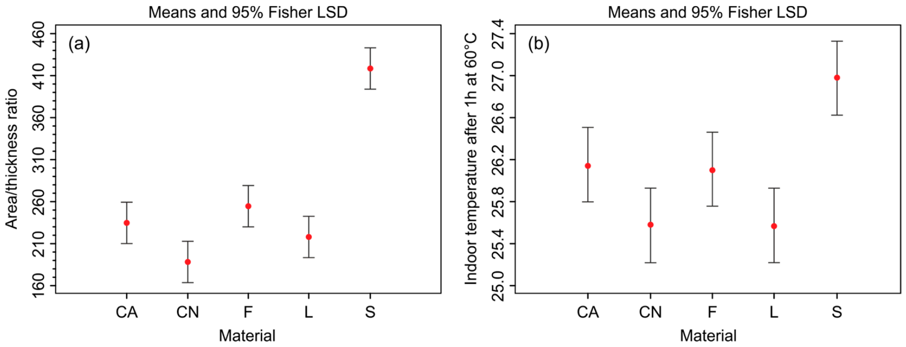

Figure 6. (**a**) Graph with averages of the area/thickness ratio for each type of insulation material. (**b**) Graph with averages of the maximum indoor temperature after 1 h at 60 °C outdoor temperature for each type of insulation material: S (control), F (wood fibres), L (rock mineral wool), CN (black agglomerated cork), and CA (white agglomerated cork).

3.2. Internal Heating Source

In the winter, hives should be designed to retain as much internal warmth as possible. To study this, we also conducted a supplementary experiment by placing a heat source inside the hives and monitoring their internal temperatures over time. Figure 7 shows the humidity and temperature graphs obtained in internal heating tests with the control hive (without insulation) and a hive with black agglomerated cork insulation.

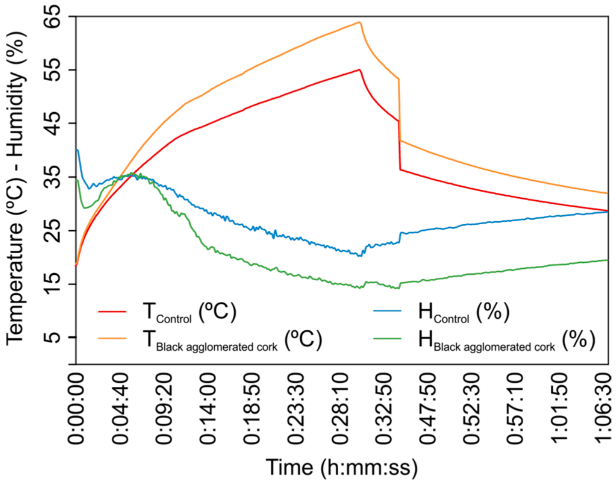

Figure 7. Plots of relative humidity (%) and temperature (°C) inside the control hive and with black agglomerated cork in the 30 m of exposure to internal heating by the infrared lamp and another 30 m of cooling.

The hive without an insulating layer exhibits a higher humidity than its counterpart equipped with black agglomerated cork. During the cooling phase, the humidity in the non-insulated hive approaches 30% after 30 min, while in the hive with black agglomerated cork, it remains at about 20%.

The temperature data reveals a 10 °C discrepancy between the control hive and the hive insulated with black agglomerated cork after a span of 30 min. Hives with this insulation achieve a temperature of 30 °C more swiftly than the control hive and manage to sustain this warmth throughout the cooling phase. A similar observation emerges from the external thermal images. As depicted in Figure 8, 30 min postexperiment, the control hive, with its lighter hues, records an average temperature of 25 °C in its warmest zones. In contrast, the hive insulated with black cork showcases darker shades, indicative of a cooler exterior surface temperature, averaging around 18 °C.

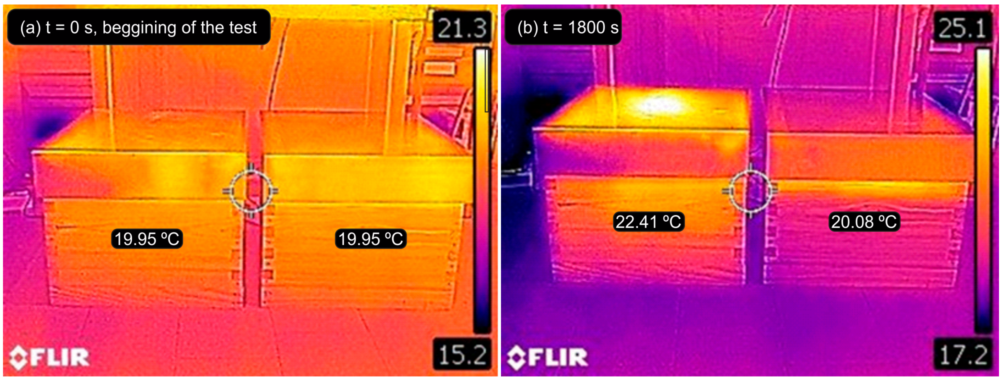

Figure 8. Images of the thermal camera test of the left control hives and right hives with black cork insulation: (**a**) at the beginning of the test and (**b**) after 30 min of heating.

4. Discussion

4.1. External Heating Source

The study's initial hypothesis—that hives insulated with specific materials would exhibit superior insulation properties compared to control hives—has been substantiated. Across various experiments and materials, insulated hives consistently outperformed control hives, with no significant differences observed between replicates. Notably, control hives showed a larger temperature variation and a higher area/thickness ratio, underscoring the enhanced insulation capability of the selected natural fibres.

The majority of specialised literature covering hive material tests has been conducted in the field with bees, which may increase the uncertainty of the analysis due to changing environmental factors or the influence of the bees on the research. The lab results here presented align with the findings of [16]. In their study, hives with black agglomerated cork had fewer thermal fluctuations throughout the day and required less time for bees to achieve the desired temperature after opening the hive. The materials chosen in this study have demonstrated their efficacy as quality thermal insulators with low thermal transmittance. This ensures that heat within the hives is maintained at temperatures lower than the control hive throughout the entire 60 min test.

Maintaining an optimal internal temperature is vital for hive habitability. The ideal internal temperature for the brood nest ranges between 32 and 36 °C [43], 34 and 35 °C [44], and 30.7 and 37 °C [45]. This temperature stability, known as homeostasis, is crucial for bee colonies. As noted by [46], prolonged exposure to internal temperatures above 38 °C adversely affects larval metamorphosis and brood growth and shortens the lifespan of adult bees. Therefore, in a broader context, given the escalating temperatures due to climate change, the results support the prioritisation of designing hives using natural insulators to effectively counter high summer temperatures.

Based on the results, black agglomerated cork and rock mineral wool offer the best insulation values compared to the other materials. Nevertheless, as indicated by the ANOVA analysis comparing areas relative to the insulation layer thickness, there are no significant differences among the four chosen natural materials, which exhibit similar behaviours. However, they show marked and significant differences when compared to the control hive (as seen in Table 2 and Figure 6a). This enhanced insulation, compared to the control hive, translates to reduced energy expenditure for the bee colony in combating external temperature fluctuations. This is particularly crucial during summer when bees have to fetch water to mist inside the hive, thereby lowering the temperature through evaporation [47,48]. This temperature-regulation process necessitates energy expenditure by the bees, which they achieve by consuming honey, which directly affects honey productivity.

In the course of our experiments, we observed that humidity levels in the non-insulated hive approached 30% after 30 min, whereas in the hive insulated with black agglomerated cork, humidity remained at approximately 20%. While our experimental setup was not specifically designed to control or measure humidity rigorously, these preliminary findings suggest that the insulation properties of black agglomerated cork may influence internal microclimate conditions by potentially enhancing the evaporation rate and vapour loss. Further studies with controlled humidity conditions are recommended to validate these observations and explore the implications of insulation on hive humidity dynamics in detail.

In light of these findings, it appears that any of the tested materials can significantly enhance a hive's insulation properties. Therefore, the selection of an insulation material should consider factors such as cost, mechanisation ease, and availability, with the latter varying by region.

4.2. Internal Heating Source

The significance of effective insulation in bee hives for both safeguarding bees during summer and maximising honey production aligns with the necessity to preserve internal warmth throughout winter. The hive must maintain a temperature inside the bee cluster at a level of 24–32 °C despite the considerable variation in the outside temperature [49]. Initial findings indicate that thermal insulation's physical properties could be instrumental in maintaining this warmth and supplementary experiments with internal heat sources confirm it.

These experiments, comparing hives insulated with black agglomerated cork to control hives, demonstrated the ability of black agglomerated cork not only to retain heat but also to maintain lower humidity levels. Such humidity control is critical for preventing the spread of pathogenic fungi, as emphasised by [50], and can be attributed to the inverse relationship between temperature and humidity: in an environment with a constant amount of water vapour, an increase in temperature is associated with a decrease in humidity. These findings emphasise the superior thermal insulation properties of black agglomerated cork, showcasing its ability to enhance hive thermal regulation. This advantage becomes particularly crucial during the colder months, transitioning into spring—a challenging period for bee colonies as identified by [51].

While enhancing hive insulation is primarily beneficial for bee survival during winter, increased indoor temperatures can have other repercussions. For instance, elevated temperatures during overwintering might adversely affect bee microbiota [52], accelerate the growth of the Varroa mite population [53], or prompt too-early brood restarting [54]. All these facets necessitate in-depth exploration through comprehensive field studies.

4.3. Sensing Technology

During this project, we tested a new open sensor network designed to collect environmental data, including indoor and outdoor temperature and humidity, to enhance apicultural management. The implementation of IoT sensors in hives allows for the real-time recording and transmission of key variables, providing beekeepers with invaluable data for informed decision-making. Practical applications of this technology include monitoring overheating risks [34,35], accurately estimating the foraging times of bees [55,56], anticipating swarming events [57], detecting the formation of winter clusters [58], or the appearance risk of diseases such as chalkbrood [59] caused by *Ascosphaera apis* (Maaßen ex Claussen).

The developed sensor network effectively monitors both indoor and outdoor temperatures and humidity levels, and it has the potential to integrate additional sensors to monitor a broader range of environmental parameters from a single node. The system used in our study is built on robust platforms previously utilised in river research applications [41]. Designed for low maintenance and high durability, it employs radio base nodes instead of WiFi to ensure reliability and extensive range and features a centralised gateway for efficient data transmission. Both nodes and gateways are based on open-source technology, making the system not only customisable but also fostering community involvement in its improvement.

During the deployment of this technology, we observed no gaps in the dataset or anomalies. The network is currently undergoing long-term field testing to further assess its performance. Furthermore, we aimed to make this technology affordable, targeting a cost of less than 100 EUR per apiary. This pricing strategy would significantly lower the entry barrier compared to existing technologies, making advanced monitoring accessible to a broader range of beekeepers and providing do-it-yourself opportunities for more technically skilled users.

Through the improvement of the insulation and the integration of sensor technology, we aim to provide beekeepers with better tools for managing hive health and adapting to environmental changes, thereby enhancing both thermal comfort and the overall wellbeing of the bees.

5. Conclusions

In the contemporary era, bees face multiple threats, notably due to shifting climatic conditions and the advancement of various stressors, thereby elevating the urgency to enhance their living conditions. Enhancements are vital not only to ensure their survival but also to technologically advance apiculture, a sector until the present time is characterised by low modernisation. This research showcases the potential improvement of conventional wooden Langstroth hives through the integration of a layer of lignocellulosic fibre materials used as thermal insulation. These materials hold the potential to maintain comfortable temperatures within the hive during summer and also mitigate energy expenditure for warming in winter months.

Our systematic study, which involved incorporating lignocellulosic fibre materials into a classical hive, demonstrated that any hive could be effortlessly retrofitted to enhance its insulation properties. Additionally, we evaluated the efficacy of a cost-effective sensor network, thereby facilitating remote hive monitoring, which could offer additional advantages for hive management in field conditions.

Laboratory tests, conducted under a controlled heat source within classical wooden Langstroth hives and involving various lignocellulosic fibre materials (namely, black cork, white agglomerated cork, wood fibres, and mineral wool) for thermal insulation, were compared against control hives devoid of insulation. Humidity and temperature, both inside and outside the beehive, were monitored via a sensor network, leading to the following observations:

- The implemented materials exhibited very similar results to each other and provided superior thermal insulation compared to a control hive (black agglomerated cork > wood fibres > white agglomerated cork > wood fibres > control). Every studied material improves insulation proportionally; therefore, the ultimate decision between them should consider factors like availability, cost, and mechanisation properties.
- The peak temperature variance recorded at the test's culmination between the hives with thermal insulation and the control hive was 2 °C for black cork and mineral wool and 1 °C for white cork and wood fibres—an effect that could significantly enhance the cumulative living conditions of bees.
- The low-cost sensor network and communication architecture implemented have performed outstandingly, demonstrating their potential for use in field conditions.

These findings are promising, indicating that incorporating insulation within the hive, either as an internal or external removable thermal jacket, yields substantial thermal insulation. This enables more stable thermal regulation within the hive against external temperature fluctuations, thereby the potential to enhance the bees' quality of life, ensuring better survival in the face of climate change or unstable weather conditions and providing direct benefits for the beekeeper.

In conclusion, the findings from this study validate the improvement of hive insulation and the implementation of real-time hive monitoring to track the daily cycle within each hive. Accordingly, these insights are set to notably contribute to the conservation and adaptive management of field hives. This comes with immediate potential repercussions for bee survival, enhancement in production, and a reduction in costs resulting from the prevention of unnecessary management actions.

Considering the results of this research, we are currently evaluating hives insulated with cork in the field as part of the next phase of this research line. This will enable us to assess the long-term impact of enhanced hive insulation on bee health. The field evaluation will involve testing the differences in survival rates as well as honey and propolis production. Additionally, this will allow us to compare the performance of natural cork insulation with synthetic materials.

Author Contributions: Conceptualisation, M.C.S., R.P.-J. and J.F.F.-P.; methodology, M.C.S., R.P.-J. and J.F.F.-P.; software, R.P.-J. and J.F.F.-P.; validation, M.C.S., R.P.-J. and J.F.F.-P.; formal analysis, R.P.-J.; investigation, M.C.S., R.P.-J. and J.F.F.-P.; resources, M.C.S., R.P.-J. and J.F.F.-P.; data curation, R.P.-J.; writing—original draft preparation, M.C.S., R.P.-J. and J.F.F.-P.; writing—review and editing, M.C.S., R.P.-J. and J.F.F.-P.; visualisation, R.P.-J. and J.F.F.-P.; supervision, M.C.S.; project administration,

M.C.S.; funding acquisition, M.C.S., R.P.-J. and J.F.F.-P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors received funding from the Fundación General de la Universidad de Valladolid (FunGe-UVa) for the concept test and to finance the beehive prototypes with the materials studied through the concession of a Prometeo award for the development of the prototype. J.F. Fuentes-Pérez contribution was funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101032024 (Smart Fishways) and by the project RYC2022-036557-I funded by the Ministry of Science, Innovation and Universities, the Spanish Research Agency through the State Plan for Scientific, Technical and Innovation Research 2021-2023 (MCIU/AEI/10.13039/501100011033), and cofinanced by the European Social Fund Plus (FSE+). R. de Padro's contribution was funded by the Social Council grant from the University of Valladolid.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are available upon request from the corresponding author. These data include the raw and processed datasets used in our analyses and any additional supporting information required to replicate the study's findings.

Acknowledgments: The authors would like to thank Jose Antonio Balmori Roiz for his collaboration in the thermal camera tests and Jose Alberto for his commitment and collaboration in the construction of the different prototypes and test elements.

Conflicts of Interest: The authors declare no conflicts of interest.

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