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Article

Using an Invasive Plant for Mycelium-Based Thermal Insulation Composites

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Highlights

What are the main findings?

- Mycomaterials were successfully made using *Reynoutria japonica* as a substrate.
- Their thermal insulation potential matched ones made from hemp or even PIR.
- However they had higher density and double the water absorption compared to hemp.

What are the implications of the main findings?

- Using invasive biomass reduces land-use competition and regulatory issues linked to hemp.
- Using *R. japonica* turns an ecological threat into a value-added sustainable resource.
- High hydrophilicity suggests *R. japonica* MBCs are best for moisture-controlled environments.

Abstract

Mycelium-based composites (MBCs)—biomaterials made from fungal-inoculated substrates—are promising candidates to replace conventional materials for thermal insulation. However, many MBCs are made from hemp, a plant material that is quite difficult to source in many countries for regulation reasons, and mobilizes agricultural field at the expense of food and feed crops. Meanwhile, many of our natural and urban ecosystems are subject to invasion by plants that are just burnt or even left on place, while they may be very good substrate for MBCs. This study investigated the comparative physical and thermal properties MBCs derived from two distinct lignocellulosic feedstocks: hemp shives (a traditional material) and biomass from the highly invasive species *Reynoutria japonica*. Polyisocyanurate (PIR) was included as a synthetic benchmark. The MBCs produced from *R. japonica* demonstrated as low thermal conductivity as hemp MBCs, but also as the PIR standard. However, they exhibited suboptimal physical characteristics: higher bulk density (166 vs 128 kg/m³ for hemp) and significantly greater water absorption (7.5% vs 3.5% volume uptake after 2 minutes). This suggest that they are a less viable alternative to hemp-based MBCs for heat insulation applications.

Keywords: mycomaterial; invasive plant; *Reynoutria japonica*; thermal insulation

1. Introduction

Climate change mitigation requires a significant reduction in greenhouse gas (GHG) emissions, with the energy sector—particularly household heating—being a major contributor. As a result, improving heat insulation in buildings is seen as a highly effective strategy for reducing household energy consumption. However, the materials currently used for insulation are often unsustainable. Polyurethane (PUR) and extruded polystyrene (XPS) are derived from petroleum, making them non-biodegradable, while mineral wools, such as fiberglass and rock wool, are highly energy-intensive to produce and also non-biodegradable [1]. Some of these materials can even pose health risks, such as skin irritation from fiberglass.

To address these concerns, a transition to more sustainable insulation materials is necessary. Existing alternatives like hemp, cotton, and wool offer biodegradable and renewable options [2] but

come with challenges such as limited availability, competition for arable land (especially in the case of cotton and hemp), and high costs. A particularly promising alternative is mycomaterials—insulation materials made from fungal mycelium grown on lignocellulosic substrates [3]. These materials demonstrate good thermal insulation properties, natural hydrophobicity [4,5], biodegradability (as fungal mycelium usually degrades in a matter of weeks) [6], low flammability [1], low density [7] and excellent soundproofing [8], making them a compelling solution for sustainable insulation. Many studies showed heat conductance values of mycocomposites in the same range as traditional insulation materials (0.029-0.070 W/mK) [9–15]. Beyond their potential to valorize waste, MBCs can exhibit thermal conductivity values comparable to conventional synthetic insulation material such as XPS.

A critical barrier to the large-scale production of MBCs is the sustainability and availability of their feedstocks. Most current substrates either possess low macro-scale availability or are sourced from agricultural lands, leading to direct competition with food and feed production. For instance, while sawdust is a common waste product of wood processing, its widespread use for MBCs creates competition with established, high-demand sectors such as the heating pellet industry. Similarly, substrates like cotton waste are already recycled as industrial absorbents, concrete additives, or plastic fillers. Furthermore, although hemp is recognized as a highly suitable substrate [11,16], its cultivation remains limited globally by regulatory restrictions and is rarely grown on marginal (non-agricultural) land. Consequently, achieving large-scale MBC production necessitates the identification of alternative feedstocks to alleviate the intense competition currently inherent in existing substrate re-use streams.

Conversely, a substantial and non-competitive supply of lignocellulosic material is readily available in many natural and urban environments, derived from invasive plant species. This biomass is often disposed of through simple burning or left in situ to decompose. Repurposing this ecologically disruptive resource for MBC production effectively eliminates competition with established re-use streams. *Reynoutria japonica* (Japanese knotweed), one of the world's 100 most significant invasive species [17], exemplifies this opportunity. Its aggressive spread, particularly along disturbed habitats like roadways, yields abundant, highly lignified biomass [17,18]. This lignocellulosic material is highly amenable to fungal degradation, establishing it as an excellent feedstock for mycomaterials. However, its rich tannins and polyphenols content might reduce fungal colonization rate [19], which may increase density and reduce porosity (and consequently thermal performance) of the resulting MBC.

In the present study, we evaluated and compared the key physical properties (thermal conductivity, density, and water absorption) of MBCs synthesized using a novel, non-competitive feedstock, the invasive species *R. japonica*, and benchmarked against MBCs grown on a conventional substrate, hemp shives. Polyisocyanurate (PIR) foam was included as a commercial insulation material benchmark. The high lignin content typical of the *R. japonica* stem biomass was expected to yield MBCs with a less favorable physicochemical profile for thermal insulation relative to conventional hemp shives. To circumvent this limitation and deliberately target a performance profile similar to the hemp benchmark, the study focused exclusively on the less lignified leaf material of *R. japonica* as the substrate.

2. Materials and Methods

2.1. Fungal Strain Maintenance

The fungal strain used in this study was the same as in [15]. It was collected in October 2023 in Spa (GPS 50.4735, 5.8839 Lambert 1972 257542 130281) and belonged to the species *Daedalopsis tricolor*. It was maintained in malt extract agar (MEA: 20 g glucose, 20 gram bac/plant agar, 10 g peptone, 20 g malt extract in 1 liter distilled water) at 23 °C (Thermo scientific Heraeus incubator) in petri dishes sealed with parafilm.

2.2. Spawn Preparation

Wheat grains (Mill&Mix) were soaked overnight in distilled water in a 2l measuring cylinder (VWR I213-1129) sealed with aluminum foil (VWR). After draining the water, we autoclaved the grains (Hirayama Hiclave HG 50) and inoculated them under sterile conditions with previously grown mycelium with 5x5 mm mycelium squares from the outer 1cm of colonies of *D. tricolor* grown on petri dishes. This spawn was placed in sterile petri dishes, sealed with parafilm and incubated at 30 °C for 18 days.

2.3. Substrate Preparation

Two substrate types were used for MBC production: *Cannabis sativa* shives and *R. japonica* leaves. Hemp was collected from the field, dried overnight in a stove at 60 °C, and shives were shredded with a Retsch SM-100 machine using a filter with mesh size of 4x4 mm. The shredded substrate was however rather heterogenous and made of broad range of particle size, from <1mm to 4mm. The shredded hemp was soaked in distilled water (50% v/v) for 1h, drained, and sterilized by autoclaving.

R. japonica biomass was collected on the 4/09/2023 near the water treatment station in Halen (50.9583315, 5.1147879) on a river bank where the Grote Gete flows into the Demer. We sorted out the leaf material. We then dried it for 24 hours at 70 °C and shredded, soaked in distilled water, and sterilized in the same way as hemp.

2.4. Composite Preparation

The spawn and substrate were mixed (20/80% v/v) in a 2 L measuring cylinder under sterile conditions and placed in a growth container (Unipak 5098-8: 210 ml & Ø 95 mm) with a filter (Sac O2) integrated in the lid. We prepared 5 replicates for both hemp and *R. japonica*. After 2.5 weeks of growth, the MBCs were inactivated by placing them at 60 °C for a total of 40 h and 40 min under a plate with a 4kg weight on top for compression (see Figure S3 in Supplementary Materials). The resulting materials had a cylindrical shape of 9cm diameter and 5cm thickness, and were stored in a dry place at room temperature for 94 days. We wanted to benchmark the MBCs with PIR, a good-performing, conventional insulation material. The PIR materials were cut out of an IKO enertherm comfort insulation panel by hand (the aluminum layer was removed so that the material would consist of pure PIR) at the same format. For each material type (MBC made on hemp substrate, MBC made on *R. japonica* substrate, PIR), 5 individual samples were produced.

2.5. Thickness Measurements

Material thickness was determined against a reference plane using a geodetic tape measure affixed to a rigid support (a straight wooden jig, as illustrated in Figure S4 in Supplementary Materials). Due to the inherent surface irregularities of the composites, a total of five replicate measurements were recorded for each sample: the maximum and minimum thickness, supplemented by three random point measurements. The arithmetic mean of these five readings was used to calculate the heat resistivity index.

2.6. Heat Conductivity Measurements

We measured heat conductivity using the protocol of [15] with slight modifications. The thermal performance was assessed using a transient heat transfer method. This principle involves monitoring the temperature rise within an insulated containment box when its outer surface is exposed to a constant external temperature of 65 °C for a duration of 30 minutes. The tested material serves as the primary thermal barrier between the temperature sensor inside the box (SensorBlue Brifit hygrometer, DE-PARENT-WA59, Shanghai, China) and the hot environment. A slower internal temperature increase is directly correlated with a lower heat conductance (higher heat resistivity) and superior insulating performance. To ensure the tested material was the sole determinant of heat

transfer, a specialized lid was designed to integrate the MBC samples in an airtight manner, as their surface was often irregular (refer to Figure S5 in Supplementary Materials for integration details).

To mitigate the impact of slight manufacturing variability inherent to the testing apparatus (boxes and lids), the setup was divided into two independent measurement units, each comprising a box, a lid, and a calibrated temperature sensor. Measurements of different material types were systematically interspersed between these two units, ensuring that the measurement unit itself did not exert a confounding influence on the derived heat resistivity values for any single material type. Prior to testing, both units underwent internal validation by running the experiment without an integrated sample. The resulting temperature differences over the 30-minute period demonstrated parity, showing no discernible difference beyond two decimal places, confirming the equivalent performance of the two measurement units.

All measurement runs involved the simultaneous placement of both measuring units into an oven maintained at 65 °C for 30.5 minutes. Real-time temperature dynamics were tracked via the Sensor Blue application to determine the total temperature increase. To guarantee consistent starting conditions, the measuring units (box and sensor only) were allowed to cool for approximately 3 hours between runs within a stable room environment (20 °C), ensuring all 8 runs commenced at 20 °C. This recovery period limited the experimental throughput to a maximum of four runs per day. Furthermore, the oven stability across multiple days was verified by running a Polyisocyanurate (PIR 3) reference material in the same unit each morning.

To account for variations in sample thickness due to their surface irregularities, we derived a heat resistivity index (R) for each material. This index was calculated as the product of the measured thickness (L) and the recorded temperature difference (Delta T) across the material according to equation 1:

$$\text{equation (1): } R = L * \Delta T$$

A higher R value indicates higher heat conductance (lower thermal resistance). This method offers a valid and robust comparative measure of thermal performance, although it does not yield an absolute thermal conductivity (λ value in W/mK) as defined by ISO standards.

2.7. Density Measurements

Density and water absorption capacity of the MBCs were measured using the protocol of [15] with slight modifications. For determination of density, the mass was obtained by weighing the finished materials on a precision weighing scale (Mettler Toledo “college” monobloc weighing technology). As the MBC samples exhibited significant surface irregularities and were not perfect cylinders, volume was measured via water displacement rather than geometric calculation. Each sample was submerged in a 1 L measuring cylinder, and water was added precisely to the 500 ml mark. To maintain measurement integrity and prevent the sample from rising and disrupting the water surface, the material was taped down at the base of the measuring cylinder. The volume of the displaced water (V_e) was measured after 2.5 minutes of sample submersion. The material’s volume was initially approximated as the difference between the initial volume (500ml) and the displaced water volume. To account for water absorption, the sample was rapidly surface-wiped, and the mass of the absorbed water (m_a) was determined by weighing the sample immediately before (m_1) and after (m_2) submersion ($m_a = m_2 - m_1$). The mass of water lost during the wiping process (m_l) was quantified by weighing the wiping paper before and after use. Given the density of water (1000 kg/m³ or 1 g/ml), these masses correspond to the absorbed volume (V_a) and lost volume (V_l). The true volume of the displaced water (V_w) was calculated by correcting the measured volume (V_e) for these absorption and loss factors: $V_w = V_e + V_a + V_l$. V_e was measured to the nearest 5 ml. Finally, the material density (D) was determined using the initial dry mass (m_1) and the corrected displaced volume (V_w): $D = m_1 / (500 \text{ ml} - V_w)$

The density of Reynoutria japonica substrate was measured by weighing a known volume of the grinded dry leaf litter. Density of Cannabis sativa was conducted out of literature study because not enough hemp shives were in stock for this measurement.

2.8. Water Absorption Measurements

Relative Water Absorption (A) was calculated using the absorbed water volume (V_a) obtained during density measurements, normalized by the material volume (V_m): $A = V_a/V_m$. This index measures the material's water uptake capacity. A complementary experiment was conducted on the raw substrates to determine their intrinsic water absorption, enabling an assessment of the mycelium's impact on reducing moisture uptake. The substrate protocol involved: weighing the dry substrate (20 ml in a 100 ml cylinder); adding water to the 70 ml mark with a 1-minute pause for initial absorption; and finally, rapidly removing excess water after 2.5 minutes via sieving. The difference between wet and dry mass provided the absorbed water mass (V_a), from which the Relative Water Absorption was calculated for both substrates and composites.

2.9. Statistics

Statistical analysis were carried out using R 4.2.2 was used for statistical analysis [20]. Normality was checked with a Shapiro-Wilk test. We used an ANOVA to test the effect of substrate on the three response variables (heat conductance, substrate resistivity and water absorption). The LDuncan function within the Laercio package was used to perform post-hoc tests.

2.10. GenAI

Artificial intelligence has been used to improve the grammar, spelling and overall readability of the text.

3. Results

3.1. Heat Resistivity

The MBCs had slightly significantly lower thermal resistance than PIR, with average index $\pm$ standard deviation of 0.46 $\pm$ 0.04 (*F. japonica*), 0.45 $\pm$ 0.02 (*C. sativa*), and 0.53 $\pm$ 0.05 (PIR) (Figure 1). There was no significant difference between the two MBCs, and both had significantly lower R index than PIR (Figure 1).

3.2. Density

The three categories of tested materials exhibited low but significantly different densities (Kruskal & Wallis rank sum test, $p=0.001$), with average index $\pm$ standard deviation of 166 $\pm$ 7 kg/m³ (*F. japonica*), 128 $\pm$ 10 kg/m³ (*C. sativa*), and 35 $\pm$ 5 kg/m³ (PIR) (Figure 2). Density of *R. japonica* substrate is: dry=200 kg/m³, wet=700 kg/m³ (after 1 h soaking in distilled water).

3.3. Water Absorption

We first measured the water absorption of the substrate alone. The *R. japonica* dried leaves absorbed more water than *C. sativa* shives (69%: 13.82 ml water/20 ml substrate, 56%: 11.22 ml water/20 ml substrate, respectively). As for the MBCs, the ones made using *R. japonica* as substrate absorb significantly more water (7.2 to 2.1%) than the ones made using *C. sativa* (3.3 $\pm$ 0.5%) and the latter in turn much more than PIR materials (0.6 $\pm$ 0.1%).

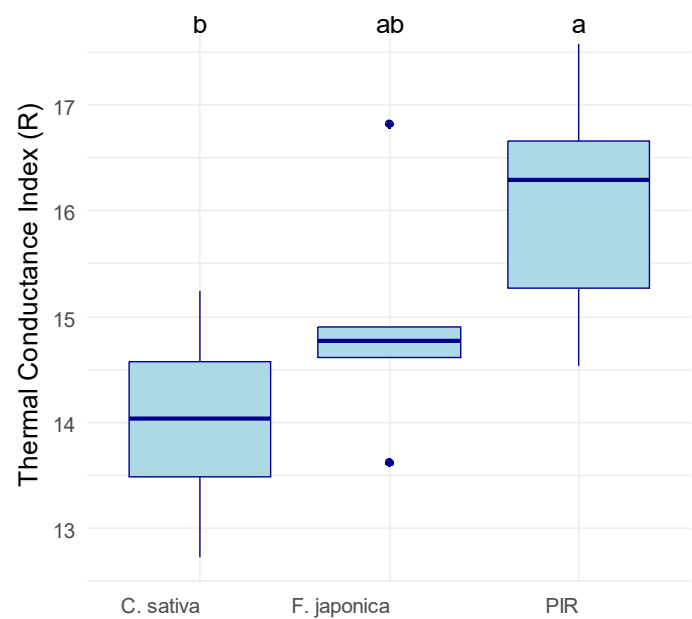


Figure 1. Thermal conductance index (R) of the tested material samples. The R index was calculated as the product between thickness (cm) and temperature difference (°C): the lower R, the lower the heat conductance, and the better the material performs for insulation. C. sativa = mycelium-based composite with Cannabis sativa shives as an inoculation substrate, R. japonica = mycelium-based composite with Reynoutria japonica leaf litter as an inoculation substrate, PIR = pure polyisocyanurate. The material had a significant impact on thermal resistance index according to an ANOVA (p=0.046). Letters on top of the box plots indicate significantly separate groups based on Tukey’s post-hoc test.

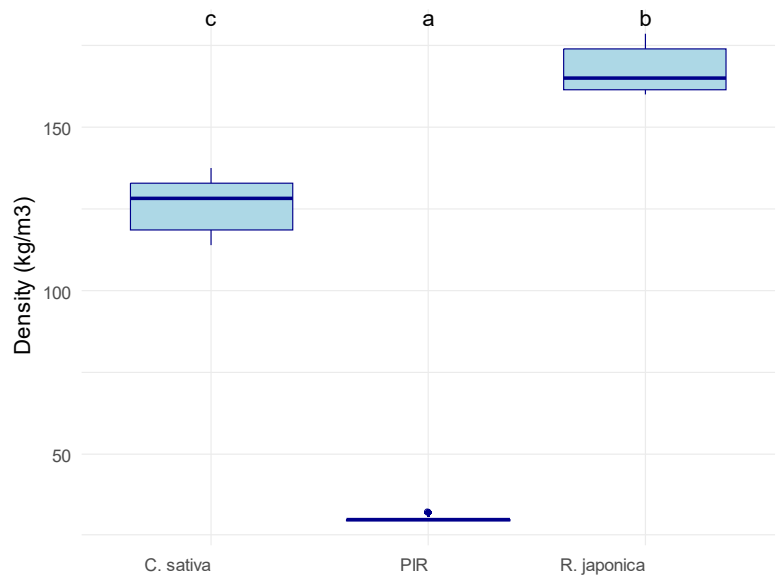


Figure 2. Density of the tested material samples. C. sativa = mycelium-based composite with Cannabis sativa shives as an inoculation substrate, R. japonica = mycelium-based composite with Reynoutria japonica leaf litter as an inoculation substrate, PIR = pure polyisocyanurate. The material had a significant impact on density according to a Kruskal & Wallis rank sum test (p=0.001). Letters on top of the box plots indicate significantly separate groups based on Tukey’s post-hoc test.

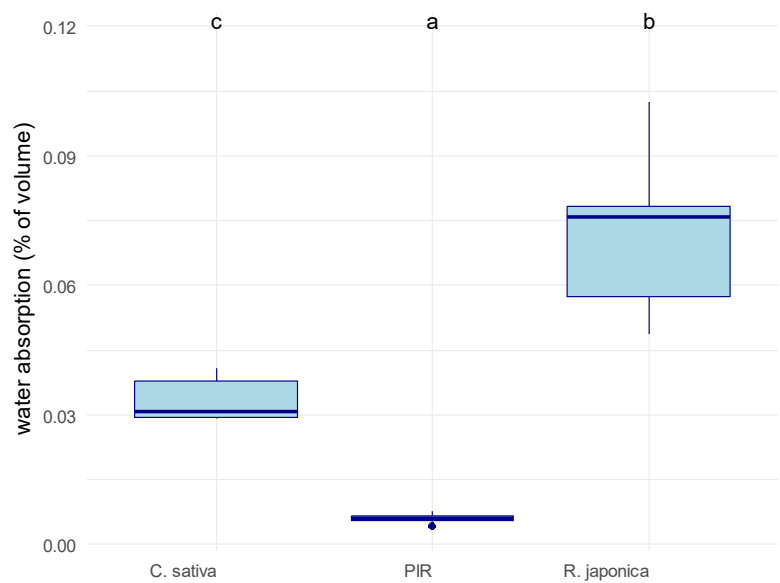


Figure 3. Water absorption of the tested material samples. Water absorption was calculated as %volume of material occupied by water after being submerged for 2 min 30 sec in water. C. sativa = mycelium-based composite with Cannabis sativa shives as an inoculation substrate, R. japonica = mycelium-based composite with Reynoutria japonica leaf litter as an inoculation substrate, PIR = pure polyisocyanurate. The material had a significant impact on water absorption according to an ANOVA ($p=8.4e-06$). Letters on top of the box plots indicate significantly separate groups based on Tukey’s post-hoc test.

4. Discussion

4.1. Good Thermal Performance of the R. japonica MBCs

Our findings demonstrate that *R. japonica* leaf biomass is an entirely compatible and effective substrate for generating MBCs suitable for thermal insulation applications. This substrate required no adaptation to the standardized bioprocessing procedure established for the widely used hemp shives [19], confirming that the plant does not secrete significant fungicidal or fungistatic compounds that would inhibit fungal colonization.

In terms of thermal performance, MBCs fabricated from *R. japonica* leaves exhibited thermal conductance levels statistically similar to those of the hemp shive MBCs and of PIR (the MBCs made of hemp, however, performed even better than the synthetic material). Considering both this result and the established thermal conductivity (λ) range of PIR (0.023-0.028 W/(m·K)), we estimate the thermal conductivity of the *R. japonica* MBCs to be in the same range. This is significantly below what is reported in literature on mycomaterials, which is typically ranging between 0.029 and 0.081 [9–14,21]. They are however consistent with previous work in our lab, and critically, were obtained using the same, unique fungal strain not employed in other research (*Daedalopsis tricolor*) [15]. Our findings clearly show that the fungal strain is a strong determinant of the MBC’s thermal conductivity. Furthermore, they suggest that this specific strain exhibits previously unobserved heat insulation potential.

Crucially, the bioprocessing step itself significantly enhances the insulating properties of the raw biomass. The thermal conductivity for the C. sativa MBCs represents an drastic reduction in thermal conductivity compared to pure hemp shives, which typically exhibit a λ value of 0.052 W/(m·K)[16]. Collectively, these results strongly support the use of *R. japonica* leaves as a viable, high-performance alternative substrate to hemp shives. Its successful integration into the standard

bioprocess confirms that this plant can be utilized as a substrate without compromising the final product's thermal resistivity.

4.2. Higher Density

Despite comparable thermal performance, the MBCs exhibited several suboptimal physical parameters, particularly concerning density. The bulk density of the materials was successfully validated against established literature values: PIR density (28-32 kg/m³) aligns with reported values (30 kg/m³), confirming the reliability of our measurement protocol. As anticipated, PIR was significantly lighter, with a density 4- to 6-fold lower than the MBCs. The observed density range for the two MBCs (*C. sativa*: 114-133 kg/m³; *R. japonica*: 160-179 kg/m³) is consistent with other published MBC data [15,22]. However, the *R. japonica* MBCs were approximately 30% denser than the *C. sativa* ones, highlighting the critical influence of the raw substrate on the final composite density. This 30% difference mostly originates from the source material: the *R. japonica* leaf biomass (200 kg/m³) was 71% denser than the *C. sativa* hemp shives (117.5 kg/m³, [23]). The elevated density of the *R. japonica* MBCs presents potential limitations for practical construction application. First, it increases the load imposed on building supporting structures, potentially requiring costly adaptation, particularly in roof or ceiling applications. Second, it complicates transportation and installation, leading to higher overall project costs.

4.3. Higher Water Absorption

Water absorption capacity differed significantly among all material types, successfully confirming the hypothesis that substrate choice dictates material hydrophobicity. The synthetic standard, PIR, exhibited exceptionally low water absorption, retaining only 0.4% to 0.8% of its own volume in water. This is approximately 5- to 10-fold lower than the absorption measured for both the *C. sativa* and *R. japonica* MBCs. Despite the MBCs showing higher overall water uptake than PIR, a crucial finding is the significant enhancement of hydrophobic properties achieved through fungal colonization. The bioprocessing dramatically reduced the hydrophilic nature of the raw substrates: relative water absorption in the raw *C. sativa* substrate dropped from 56% to 2.9%-4.1% after colonization. In the raw *R. japonica* substrate, absorption decreased from 69% to 4.9%-10%. This considerable reduction is likely attributable to the extensive formation of hydrophobic mycelial biomass, in particular the formation of a fungal skin on the MBC surfaces [24], which physically repels water. The hierarchy of water absorption is governed by the fundamental chemical composition of the materials: PIR is inherently highly hydrophobic due to its composition of synthetic polymeric monomers. MBC Substrates are composed of naturally hydrophilic plant biomass, stemming from their high content of polar biopolymers, primarily cellulose and hemicellulose. The *C. sativa* shives contain a relatively high content of lignin [25]. As a significantly more hydrophobic class of organic polymer compared to (hemi)cellulose, lignin provides greater inherent resistance to water. Conversely, the dried *R. japonica* leaf substrate is expected to possess lower lignin content and higher concentrations of hydrophilic biopolymers, probably explaining its higher water absorption.

This has consequences for real-world applications, where insulation materials are frequently subjected to heat/cold cycles that induce condensation and subsequent water uptake. This moisture ingress not only reduces thermal resistance but also elevates the risk of biological degradation (moulding). Consequently, minimizing water absorption is crucial for insulation durability. While the brief water submersion test does not precisely replicate the long-term, dynamic conditions of condensation, these results are a good indicator of performance under extreme exposure. The data confirms that PIR significantly outperforms the MBCs in water resistance, and within the biocomposite group, the *R. japonica*-based MBCs perform significantly worse than their hemp alternative.

Collectively, these data confirm that producing MBCs from *R. japonica* biomass is as easy as with any other lignocellulosic substrate and yields materials with the same heat insulation performance, their high density and water absorption makes them a less optimal alternative.

4.4. Risks of Working with *R. japonica*

We would moreover advise against the widespread use of this species as a commercial substrate due to significant ecological and potential health risks. This plant is globally recognized as a highly invasive species, notorious for causing substantial damage to native biodiversity and infrastructure [26]. Its primary mode of proliferation is highly efficient vegetative spread via rhizome and plant fragments. Consequently, any large-scale harvesting or collection efforts for MBC production carry a critical risk of inadvertently promoting the dispersal of invasive fragments, thereby exacerbating biodiversity loss. Furthermore, efforts to commercially valorize the biomass as an insulation material could unintentionally diminish control efforts aimed at managing the invasive species or create economic incentives for its deliberate cultivation and dissemination. Its use as an MBC substrate therefore represents a significant ecological threat rather than a sustainable service to biodiversity.

5. Conclusions

This study successfully demonstrates two key findings: that substrate choice significantly impacts the final MBC properties and that dried *R. japonica* leaf material can be a highly effective and interesting form of lignocellulosic substrate for mycelium-based composites. Given the demonstrated feasibility, future research should focus on exploring the use of leaf litter or biomass from non-invasive plant species to mitigate the ecological risks identified in this study.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, K.D, J.V. and F.R.; methodology, K.D, J.V. and F.R.; validation, K.D, J.V. and F.R.; formal analysis, K.D.; investigation, K.D.; resources, F.R.; data curation, K.D. and F.R.; writing—original draft preparation, K.D.; writing—review and editing, K.D. and F.R.; visualization, K.D and F.R.; supervision, F.R. and J.V.; project administration, F.R.; funding acquisition, F.R. All authors have read and agreed to the published version of the manuscript.”

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

Abbreviations

The following abbreviations are used in this manuscript:

MBC Mycelium Based Composite

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