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BUILDING SUSTAINABILITY: INTEGRATING AGRICULTURAL AND INDUSTRIAL SUB-PRODUCTS IN THE BUILDING SECTOR

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Abstract

The construction sector demand for thermal insulation materials is rising, to enhance building energy efficiency and indoor thermal comfort. While insulation materials like organic foams (EPS, XPS, PUR, PIR) or inorganic fibers (glass or rock wool) are widely used, there is a shift towards eco-friendly alternatives derived from agro-industrial waste. These sustainable options not only reduce operational energy consumption in buildings but also offset some of their own production energy requirements. Furthermore, using such sub-products as insulation materials presents an ecological advantage, contributing to CO_2 sequestration and offering a greener choice in the construction industry. This paper presents the thermal properties of such insulating materials and compares their values with some of the commonly used insulation materials. The thermal conductivity of the materials was assessed using the λ-Meter EP500e, a guarded hot plate apparatus specialized for such measurements, using the instructions outlined in the SR EN 12667 standard, ensuring accuracy and compliance with established guidelines. The paper aims to elevate awareness about the potential of transforming what is currently viewed as agricultural waste into innovative and environmentally friendly building materials.

***Key words**: agricultural sub-products, building insulation, thermal conductivity, sustainability.*

INTRODUCTION

Taking on and contributing to the achievement of the 17 Sustainable Development Goals is a global and, implicitly, a national priority. In this context, there are four key areas where materials intended for the thermal insulation of buildings have a significant impact: the efficiency of energy consumption that is required to ensure the comfort of the population; the quality of air in living spaces to maintain hygiene and health conditions of the population; sustainable use of natural resources; and environmental impact. Thus, there is a dual focus: on one hand, towards the production of heat-insulating materials with the highest possible performance in terms of thermal insulation, and on the other hand, the increasing need to identify possibilities for creating new, more environmentally friendly heat-insulating materials. These materials should allow for the recycling of industrial waste or by-products and contribute to improving air quality in living spaces. Currently, the market offers a variety of classic heat-insulating materials, such as expanded or extruded polystyrene, mineral wool, and polyurethane foam, most often available in the form of plates to facilitate installation. Additionally, there are several "niche" materials gaining prominence, made from either vegetable or animal fibers or by recycling waste from various industries (e.g., cardboard and paper waste, cigarette manufacturing waste, wood waste).

The specialized literature highlights the following:

- Estimates up to 2020 suggest that buildings account for 30-40% of total global primary energy consumption and over 25% of greenhouse gas emissions (Ricciu et al., 2018; Dodoo et al., 2011; Csanády et al., 2021).
- Thermal insulation based on expanded or extruded polystyrene, polyurethane foam, glass fiber wool, or mineral wool accounts for approximately 87% of the market (Ahlberg et al., 2014; Stevulova et al., 2013).
- Some classic thermal insulation materials, despite their cost-effectiveness and

ease of installation, have disadvantages such as low biodegradability and limited post-use possibilities. Being slightly permeable to gases and water vapors, they could negatively affect indoor air quality by trapping water vapor, volatile organic compounds, radon, or other harmful gases for extended periods. Increased air humidity can also promote the growth of mold on interior wall surfaces, potentially leading to "sick building syndrome" (Maskell et al., 2015; Mølhave et al., 1997; Curling, 2012; Mansour et al., 2016; Salthammer et al., 2010; Takeda et al., 2009). Buildings affected by microbial deposits can experience a decline in indoor air quality due to spore contamination and toxin release. Common mycotoxins found in indoor air and within populations residing in contaminated environments - produced by molds such as *Cladosporium*, *Acremonium*, *Alternaria*, *Periconia*, *Curvularia*, *Stemophylium*, *Penicillium*, *Aspergillus* - include ochratoxin (OCT), aflatoxin B1, and trichothecenes, known for their genotoxic, immunotoxic, hepatotoxic, mutagenic, and potentially carcinogenic effects (Khan et al., 2012; Hope et al., 2013; Zukiewicz-Sobczak et al., 2013; Andersen et al., 2011).

- Research into the production of innovative thermal insulating materials from fibers and agricultural waste, of vegetable or animal origin, or from waste and by-products of other industries, presents new challenges, especially in terms of ensuring satisfactory resistance to micro-organisms and good water behavior, i.e., low absorption in case of accidental immersion (Zach et al., 2013; Vėjelienė et al., 2011).

- According to national and international regulations, thermal insulation materials must meet specific thermal performance requirements as well as minimum fire resistance standards (Chereches et al., 2021; Ciobanu & Puscasu, 2013; Bode et al., 2023; Simion et al., 2019; Thieblesson et al., 2024; Kušnerová et al., 2018).

- In the case of "niche" heat-insulating materials, the most common antifungal treatments, which also serve to increase fire resistance, include those based on borax, boric acid, aluminum sulfate, or ammonium sulfate (Day et al., 1981; Herrera, 2005), typically applied through wet spraying. However, research has indicated that these treatments have limited durability, may impact population health, and have a less favorable environmental impact (Papoutsis et al., 2019; Liu et al., 2018; Dai et al., 2022). Moreover, antifungal treatments, like any other treatment intended to enhance durability, fire resistance, etc., must adhere to EU regulations concerning the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH). This is crucial to prevent threats to human health and the environment.

- Another significant aspect of experimental research concerns the variation in the thermal conductivity coefficient, influenced by either the material's moisture content or the temperature range within which the thermal conductivity coefficient is determined. Vejelis et al. (2006) demonstrated that a 1% increase in hygroscopic moisture content leads to a 1.25%-2% increase in the thermal conductivity coefficient (λ). This finding aligns with earlier research by Sandberg (1992), who formulated a linear equation to describe the variation of the thermal conductivity coefficient as a function of the insulating material's water absorption, as follows:

$$\lambda=0.037+0.0002w \text{ (W/mK)} \quad (1)$$

where:

- w represents the amount of water absorbed per unit volume of cellulose, in kilograms per cubic meter (kg/m^3).

Finally, research by Talukdar (Talukdar et al., 2007) also indicated that the thermal insulation performance, quantified by the thermal conductivity coefficient and measured across a temperature range of 10°C to 30°C, with an average temperature of 22.5°C, varies according to a polynomial function in relation to the moisture content (φ). This dependence can be expressed by a non-linear function of the form:

$$\lambda=(a+b\varphi+c\varphi^{1.5}+d\exp(-\varphi)) \quad (2)$$

where:

-a, b, c and d are experimentally determined coefficients, with the values: a = 0.092482655, b = 0.15480621, c = 0.066517733 and d = 0.1296168.

The aim of this paper is to conduct a comparative analysis of the resistance of various heat-insulating materials available on the Romanian market to humid environments

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and environments contaminated with mold spores. These materials include those found in the category of "classic" materials, such as expanded polystyrene, mineral wool, and polyurethane foam, as well as "niche" materials produced by recycling cellulosic waste and using vegetable or animal fibers.

MATERIALS AND METHODS

The experimental research was conducted at a constant temperature of 23°C ± (0.25 to 0.3)°C, aiming to evaluate the behavior of certain heat-insulating materials used in construction under conditions of high humidity and/or contamination with mold spores. The selection of these materials aimed to compare classic, commonly used materials (expanded polystyrene, mineral wool, polyurethane foam) with "niche" materials made from raw materials of vegetable origin (wood fiber waste), animal origin (sheep's wool), or by recycling various wastes (acrylic-cellulosic waste from cigarette filters, cellulosic cardboard waste, siliconized paper from printing waste, and aluminized polyethylene film from printing waste). The materials were analyzed as received from the manufacturers, without any further processing or treatment prior to testing. They were coded according to Table 1.

Table 1. Codification and characterization of heat-insulating materials

Sample Code	Installation Method	Raw Material
P1	External cladding in ETICS system	Expanded polystyrene
P2		Mineral wool
P3		Polyurethane foam
P4	Inside the structure, loose-fill, between rigid panels	Processed wood fibers (shredded)
P5		Cellulose acetate, waste from cigarette filter manufacturing
P6		Non-woven sheep wool insulation mat
P7		Cellulose from cardboard waste
P8		Waste from silicone-coated paper printing
P9		Waste from polyethylene film printing
P10		Waste from printed aluminized polyethylene film

The methodology of the work included the following stages:
1. Visual characterization;
2. Determination of apparent density, according to EN 1602;
3. Analysis of water behavior by determining water absorption through the short-term (24 h) partial immersion method, according to EN ISO 29767 for materials with a defined shape (expanded polystyrene, mineral wool, polyurethane foam, and heat-insulating sheep wool mattress). For bulk materials of ligno-cellulosic or animal origin, the sorption-desorption capacity was evaluated according to EN ISO 12571. For waste from the printing industry (silicone paper [P8], polyethylene foil [P9], and aluminized polyethylene foil [P10]), this experimental testing was not applicable as these materials are hydrophobic.
4. Characterization of thermal insulation performance by determining the coefficient of thermal conductivity, λ_{10}^{ct}. (W/mK), using a λ-Meter EP500e conductivity meter (Lambda-Messtechnik GmbH, Dresden, Germany) in accordance with EN 12667. Samples were dried to a constant mass in a ventilated oven, and testing was performed at an average test plate temperature of 10°C ± 1°C.
5. Characterization of the materials in terms of resistance to mold action, in two test variants:
- Variant 1: Analysis of the risk of mold occurrence in case of exposure to high humidity conditions, following the work methodology specific to the evaluation of the biological resistance of thermal insulation or acoustic insulation materials, made of animal fibers, either manufactured in the factory or in-situ, as indicated in references EAD 040005-00-1201 and EN ISO 846. Accordingly, the samples were exposed in an environment with high humidity resulting from the evaporation of water at normal atmospheric pressure and a constant temperature of 23°C ± 1°C, within a closed enclosure, for 28 days. At the end of the exposure period, the samples were analyzed visually without optical magnification and microscopically with the aid of a LEICA SAPO microscope, to identify any signs of mold development. The resistance to the action of microorganisms was quantified by assigning rating classes of fungal growth and categories that indicate the performance in terms of nutrient content conducive to the development of microorganisms, in accordance with EN ISO 846, summarized in Table 2.
- Variant 2: Analysis of resistance to mold when exposed to an environment heavily

contaminated with spores of *Penicillium notatum* and *Aspergillus niger*. To achieve this, culture systems were established: each type of sample was placed in a Petri dish on a nutrient substrate of potato dextrose agar (PDA) (39 g/l). A solution containing spores of *Penicillium notatum* or *Aspergillus niger* (10 μl/10 ml distilled water) was sprayed onto the tested sample and the nutrient substrate, from a perpendicular distance of 100 mm. The entire system was sealed and incubated at a constant temperature of 23°C ± 1°C in a BIOBASE BOV-D30 incubator. The system was evaluated at regular intervals to monitor the appearance and development of mold and the extent of coverage on the material sample's surface. This was done through microscopic evaluation using a LEICA SAPO microscope. For quantification, a system similar to that used in Test Variant 1 was adopted, as detailed in Table 3.

Table 2. Evaluation of fungal growth and product performance

Class	Fungal Growth Evaluation	Category	Product Performance Estimation
Class 0	No signs of growth under microscopic examination.	0	The material does not provide a nutrient medium for microorganisms (it is inert or fungistatic).
Class 1	Growth not visible to the naked eye, but clearly visible under a microscope.	1	The material contains few nutrients or is so minimally contaminated that it only allows for very limited development.
Class 2	Growth visible to the naked eye, covering up to 25% of the test surface.	2-3	The material does not resist microbial attacks; it contains nutrients that allow their development.
Class 3	Growth visible to the naked eye, covering up to 50% of the test surface.		
Class 4	Growth visible to the naked eye, covering more than 50% of the test surface.		
Class 5	Strong growth covering the entire test surface.		

Table 3. Evaluation of resistance to fungal action in heavily contaminated systems

Classification of the resistance to fungal action	Evaluation
Very High	No signs of growth, with possible punctate signs visible only under a microscope, of mold growth on the analyzed surface.
High	Biofilm covering less than 50% of the analyzed surface, or microscopic analysis reveals visibly intense signs of mold anchoring on the fibers/granules of the material.
Medium	Biofilm covering 50% - 75% of the analyzed surface.
Low	Biofilm covering more than 75% of the analyzed surface.

RESULTS AND DISCUSSIONS

The experimental results concerning thermal insulation performance and resistance to mold action, which have implications for both the compatibility of the materials with their intended use (building insulation) and the quality of indoor air, revealed similarities and differences among the 10 types of materials analyzed. It is believed that these performances are influenced by several factors, with the characteristics of the raw material used to produce the material being the primary element.

The apparent density of the materials is a significant characteristic as it has implications including the degree of additional load on the building's structural integrity. As illustrated in Figure 1, generally, this parameter falls within limits indicating that using these materials for thermal insulation does not significantly stress the structural integrity, with most of them being relatively lightweight. Mineral wool is the densest material among those analyzed, but its density is still far below that of materials typically used for constructing self-supporting walls, such as concrete, which has a density 25 times greater.

Short-term water absorption determined by partial immersion, as shown in Figure 3, indicated that all the analyzed materials - those available in defined shapes, such as tiles or mattresses - have values below 1 kg/m². Among these, the sheep's wool mattress (P6) exhibited the highest water absorption rate at 0.6 kg/m². In contrast, the polyurethane foam insulation, due to its closed-cell structure and the material's water-repellent characteristics, displayed the lowest absorption rate at 0.02 kg/m². This measure is particularly relevant in scenarios where accidental water contact occurs. The sheep's wool mattress, absorbing a larger amount of water, is subject to more significant variations in terms of the thermal conductivity coefficient, which is known to be influenced by the moisture content of the material (Sandberg, 1992). Conversely, polyurethane foam, being minimally affected by water, will consequently demonstrate greater stability in thermal insulation performance, as quantified by the thermal transfer coefficient.

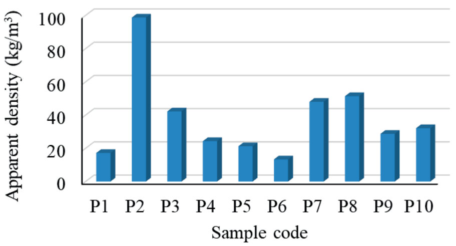

Figure 1. Apparent density

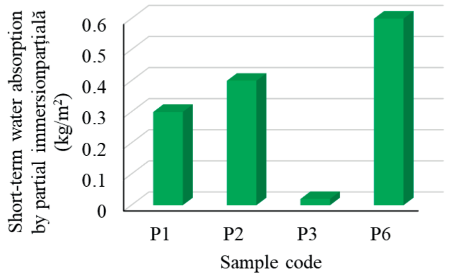

Figure 2. Short-term water absorption by partial immersion

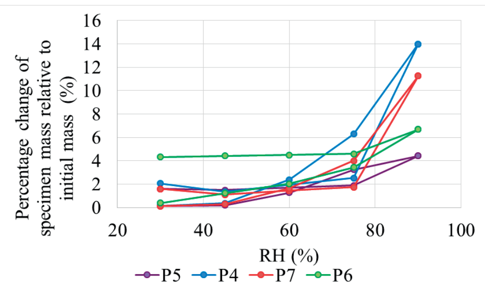

Figure 3. Percentage change in specimen mass relative to initial mass

The hygroscopic nature of the bulk thermal insulation materials (of undefined shape), including the sheep wool mattress, was analyzed using the percentage variation of the specimen's mass relative to its initial mass (representing the amount of adsorbed/desorbed water) as a function of the relative humidity of the air, w (%) = f (RH(%)), as shown in Figure 3. The four materials analyzed - wood fibers processed by chopping (P4), cellulose acetate from cigarette filter manufacturing waste (P5), non-woven sheep wool mattress (P6), and cellulose from cardboard waste (P7) - demonstrate a relative consistency in the sorption phenomenon, with a slight increasing trend up to an RH of 75%, followed by a marked increase in the sorption phenomenon in the relative air humidity range of 75% - 90%. Examining the desorption diagram for each material type reveals a difficulty in water loss around a real air humidity of 75%. Thus, it is inferred that materials at a 75% relative air humidity retain a larger amount of water, and part of the water adsorbed at the maximum RH (90%) is not released back into the environment when the RH decreases to 75%. Upon examining the sorption/desorption curves (Figure 5) for the bulk materials made from waste (P4, P5, P7), an intersection point between the ascending curve (sorption) and the descending curve (desorption) is observed in the 50%-70% relative air humidity range. For each material, the intersection point is positioned at a specific humidity: about 55% for wood fiber-based material (P4), about 65% for cigarette filter manufacturing waste-based material (P5), and about 67% for cardboard waste-based material (P7). Conversely, for the sheep wool-based material (P6), the characteristic sorption and desorption curves do not intersect, and the sorption curve lies below the desorption curve. This pattern indicates the capacity of the materials to release stored water, although limited. Nonetheless, it suggests that under conditions of indoor air humidity variation (a parameter of indoor air quality), these materials could help regulate this indicator and, by extension, contribute to improving air quality. However, in line with the specialized literature (Rode, 1998; Vrana & Gudmundsson, 2010), the limited ability to release absorbed moisture may lead to moisture accumulation within the thermal insulation material, potentially fostering conditions conducive to mold growth.

In terms of thermal insulation performance, as depicted in Figure 4, it is estimated that all analyzed materials meet the expectations for their intended use, with the coefficient of thermal conductivity ranging from 0.035 W/mK for mineral wool (P2) to 0.056 W/mK for sheep wool insulation (P6).

Analyzing the two key indicators for the materials - apparent density and the coefficient of thermal conductivity, as shown in Figure 5, it can be first noted that the nature of the material significantly influences these properties. Additionally, advantages and disadvantages can be identified for each specific case. For instance, among the analyzed materials, the sheep wool mattress (P6) has the lowest density but exhibits the least favorable performance in terms of thermal insulation, having the highest value for the coefficient of thermal conductivity. Conversely, mineral wool (P2) possesses the highest density, approximately 7 times higher than that of the sheep wool mattress, yet demonstrates superior thermal insulation performance, with a thermal conductivity coefficient 37.5% lower than that of the sheep wool mattress, which is the highest among the analyzed samples.

The cases of polyurethane foam (P3) and expanded polystyrene (P1) are also notable. Despite its high apparent density - about 3.2 times higher than that of the sheep's wool mattress, the lightest among the analyzed thermal insulating materials - polyurethane foam offers the best thermal insulation performance, with a thermal conductivity coefficient (λ_{10}^{ct}) of 0.022 W/mK. In contrast, expanded polystyrene (P1), while having a low density close to that of the sheep wool mattress and approximately 2.5 times lower than that of polyurethane foam, which is the best performer in this study, exhibits a thermal conductivity coefficient with a value of 0.014 W/mK higher than that of polyurethane foam. Similarly, other thermal insulation materials made from recycled waste (P4, P5, P7-P10) show average thermal insulation performances, with thermal conductivity coefficients ranging from 0.038 to 0.042 W/mK, and intermediate apparent densities ranging from 21.2 to 51.4 kg/m³.

However, when analyzing the interdependence between apparent density and the thermal conductivity coefficient, it appears there is no direct correlation between the two indicators; a function of λ_{10}^{ct} = f (density) cannot be clearly identified. This shows that the thermal performance of materials is influenced by multiple factors, not solely by density, and suggests that is impossible to correlate the thermal conductivity value with the materials density, for a range of materials.

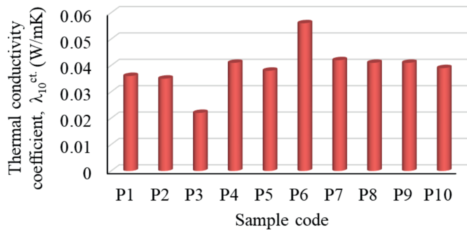

Figure 4. Thermal conductivity coefficient

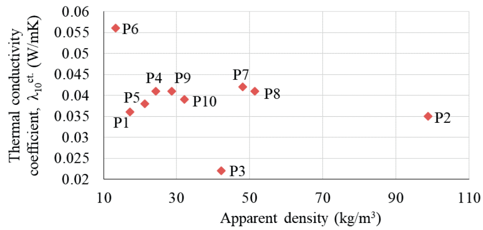

Figure 5. Variation of the thermal conductivity coefficient according to apparent density

Regarding the resistance of materials to the action of molds, significant differences are observed among the species used, influenced by several factors. On one hand, the testing methodology applies different levels of stress on the material. Variant 1 represents a moderate demand method, with a reduced mold spore load, characteristic of a high humidity environment. In contrast, test variant 2 subjects the material to high stress, with the mold spore load significantly increased, by artificial means. On the other hand, the type of material, its nature, and the characteristics of the raw material greatly influence resistance to mold action. Consequently, as shown in Table 4, the heat-insulating materials studied were identified as either belonging to the category that does not provide a nutritious environment for microorganisms (being inert or fungistatic), such as P2 (mineral wool), P5 (acetate-cellulosic material from cigarette filter manufacturing waste), P6 (non-woven sheep wool mattress), or materials that contain few nutrients or are so minimally contaminated that they only permit very limited mold development under high humidity conditions, like P1 (expanded polystyrene), P3 (polyurethane foam), P4 (wood fibers), P7 (cellulose acetate material from cardboard waste), P8 (silicone paper-type printing waste), P9 (polyethylene film-type printing waste), and P10 (aluminized polyethylene foil-type printing waste).

Table 4. Codification and characterization of thermal insulation materials

Sample code	Fungal growth evaluation (Class)	Product Performance Estimation (Category)
P1	1	1
P2	0	0
P3	1+	1
P4	1+	1
P5	0	0
P6	0	0
P7	1+	1
P8	1	1
P9	1	1
P10	1	1

Note: The "+" sign indicates cases where, although signs of mold existence and growth are not visible to the naked eye, they are more intense/numerous upon microscopic evaluation compared to the density and intensity of samples classified in class 1, without, however, meeting the criteria for classification in class 2 (visible to the naked eye).

However, it should be noted that while materials P3, P4, and P7 do not meet the criteria to be classified as materials resistant to microorganism attacks (as they contain nutrients that facilitate their development), visible signs of mold appearance and growth cannot be identified through visual examination without magnification. Nevertheless, upon microscopic evaluation, these signs are present either in higher numbers or show more intense development of punctate colonies compared to other materials in the same category.

In terms of material resistance in environments heavily contaminated with mold spores, as observed in test Variant 2 (Figures 6-8), specific observations were made for each type of material and mold species. For instance, in cases of contamination with *Penicillium notatum*, mold development was observed on the PDA nutrient substrate after 2 days of exposure, confirming the viability of the inoculum. Additionally, localized mold areas were identified on some analyzed materials, specifically on the surface of expanded polystyrene granules (P1) and on the edges of the mineral wool sample (P2). More intense signs of mold growth were seen on wood fibers (P4), cellulose acetate threads from cigarette filter manufacturing waste (P5), and cellulosic thermal insulation samples from cardboard waste (P7), with the fibers showing heavier microbiological formations, though these could not be identified without optical magnification. The samples of polyurethane foam (P3), sheep's wool (P6), siliconized paper waste (P8), polyethylene film waste (P9), and aluminized polyethylene film (P10) displayed no signs of contamination. The process of mold colonization and development continued over the 14 days of testing; some samples, like those from cellulosic cardboard waste, ended up being completely covered, while others had 50% - 75% of their surface covered by biofilm (mineral wool, siliconized paper waste, polypropylene foil waste, and aluminized polyethylene foil waste). However, no signs of mold growth were observed on the surface of expanded polystyrene, polyurethane foam, and sheep wool fibers except, perhaps, under microscopic analysis as shown in Figure 6. It's noteworthy that expanded polystyrene, polyurethane foam, and sheep wool fibers exhibited no signs of mold growth on their surfaces.

An interesting observation made during the tests involved expanded polystyrene (P1): initially, after 2 days of exposure in the contaminated environment, slight signs of *Penicillium notatum* mold anchoring were observed on the surface of the polystyrene granules (Figure 7a). However, its growth halted (Figure 7b), indicating that the expanded polystyrene substrate does not support further growth.

The resistance of materials to inoculation with *Aspergillus niger* showed better resilience, at least during the first two days of exposure, with no microscopic signs of mold growth on the surface/fibers/granules of any material. At this stage, signs of mold growth were only identified on the surface of the PDA nutrient substrate, confirming the spore viability.

After 14 days of exposure in a heavily contaminated environment, as shown in Figure 8, the presence of *Aspergillus niger* mold was observed in most of the tested materials. Exceptions, which did not show the development of this type of mold even after 14 days of contamination, include the polyurethane foam (P3) and the sheep wool mattress (P6).

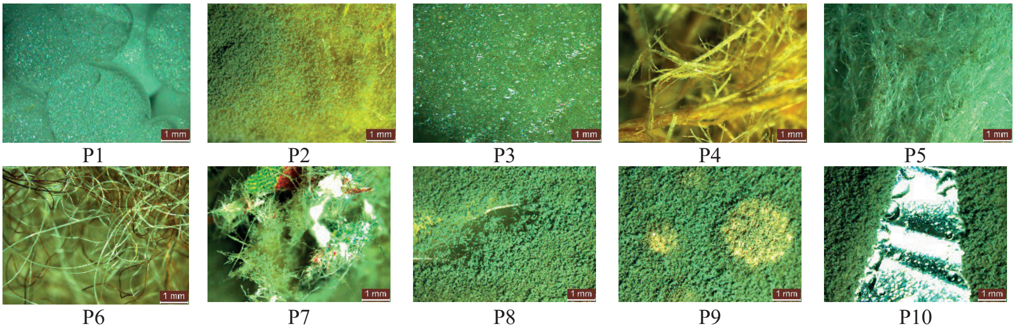

Figure 6. The appearance of the samples exposed in an environment contaminated with *Penicillium notatum* spores, after 14 days of exposure

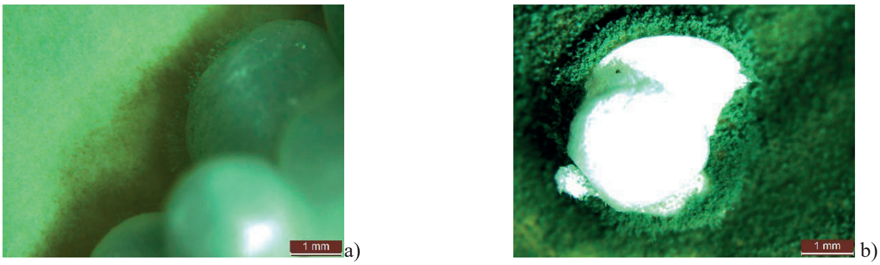

Figure 7. Appearance of the expanded polystyrene sample exposed in an environment contaminated with *Penicillium notatum* spores: a) after 2 days of exposure; b) after 6 days of exposure

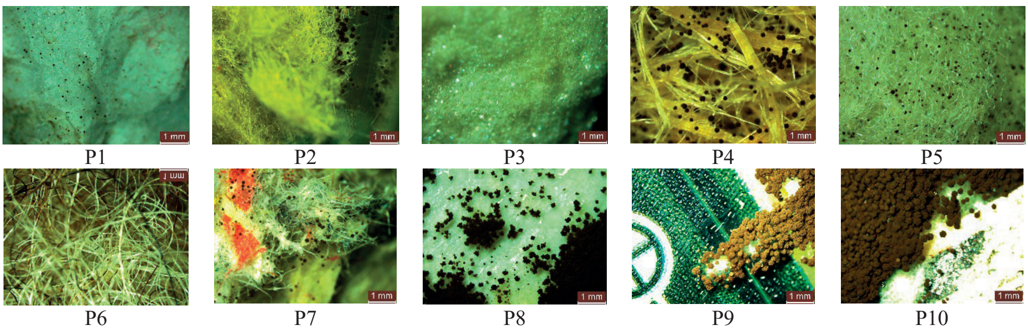

Figure 8. The appearance of the samples exposed in an environment contaminated with *Aspergillus niger* spores, after 14 days of exposure

On the surface of the expanded polystyrene (P1), only a few signs of growth could be identified. The observed differences in the development of biological contamination led to the identification of two distinct behaviors. Thus, on the mineral wool (P2) and the waste from the printing industry (P8-P10), localized mold colonies were recorded. In contrast, on the heat-insulating materials with a more fibrous structure, such as chopped wood fibers (P4), waste from cellulose acetate used in the manufacture of cigarette filters (P5), and cardboard waste (P7), mold distribution was relatively even throughout the material, showing good anchorage on the fibers.

Based on these experimental results, it is evident that a comprehensive and complex characterization of the analyzed materials can be achieved (Figure 9). This characterization can be extended to a wide range of other materials intended for thermal insulation of buildings or for protection against other types of potentially contaminating microorganisms. It allows for an analysis that acknowledges the resistance of the analyzed materials to mold action depends both on the material's nature and the exposure conditions.

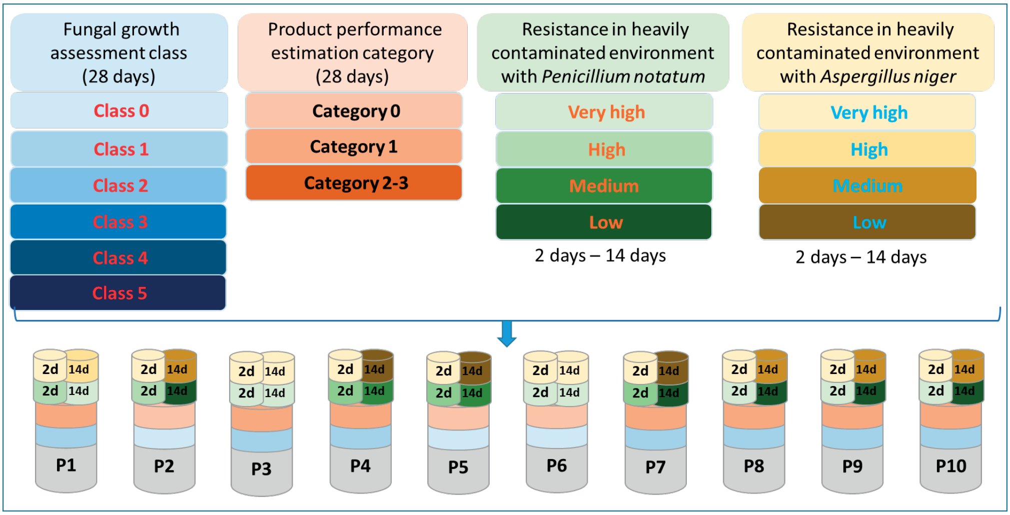

Figure 9. Characterization of materials from the point of view of resistance to the action of mold in an environment with high humidity and in an environment heavily contaminated with spores of *Penicillium notatum/Aspergillus niger*

There are cases where the same type of thermal insulation material exhibits good resistance in a humid environment but performs less satisfactorily in an environment heavily contaminated with mold spores, as with mineral wool insulation. Conversely, materials like expanded polystyrene and polyurethane foam, although highly resistant to mold action, are known to restrict "wall breathing" due to their particularly low permeability to water vapor and are also not biodegradable. This can have a less desirable effect on indoor air quality and environmental impact.

A similarly complex situation arises with sheep's wool insulation, which is permeable to water vapor and resistant to mold but has disadvantages in terms of a higher thermal transfer coefficient, indicating lower thermal insulation performance and also has restrictions in order to assure a proper installation method.

Regarding thermal insulation materials made from recycled waste, it appears that waste from the cigarette filter manufacturing process presents the most favorable option, providing an overall less conducive environment for mold development. This is also true for wood fiber waste, which ensures reasonable thermal insulation efficiency.

CONCLUSIONS

The aim of this paper was to analyze the performance and behavior of certain "niche" thermal insulation materials available in the construction market, derived from waste raw materials, in comparison to "classic" thermal insulation materials. The analysis focused on compatibility with their intended use, behavior under humid conditions, and resistance to the risk of mold appearance and development. Based on the research findings, the following conclusions can be drawn:

- From the point of view of the compatibility with intended field of use, all analyzed materials demonstrated thermal conductivity coefficients that classify them as having thermal insulating properties. It is recognized that their use can significantly contribute to reducing energy consumption by ensuring thermal comfort indoors.

- From the point of view of the behavior in direct contact with liquid water, among the four types of materials tested (those with defined shapes), a notable performance of expanded polystyrene and polyurethane foam was observed due to their granular or closed-cell structure. Conversely, thermal insulation made from animal fibers, such as sheep's wool, exhibited high water absorption due to the organic nature of the fibers. Therefore, special conditions for installation and use are necessary for thermal insulation of animal origin.
- The impact on indoor air quality from the point of view of the ability to regulate air humidity, it has been proven that the materials with an undefined shape (in bulk) analyzed materials possess a capacity for atmospheric humidity sorption and desorption, thus regulating indoor humidity. However, during the desorption process, some of the adsorbed water remains as residual moisture in the material, potentially creating an environment that allows microorganism growth.
- From the point of view of the impact on indoor air quality regarding microorganism contamination, the analysis of mold risk and resistance to mold attacks revealed a generally low risk of mold appearance under high humidity conditions, with mineral wool and sheep's wool insulation showing the best performance. However, when exposed to environments heavily contaminated with mold spores, such as *Penicillium notatum* and *Aspergillus niger*, the resistance of the same insulation materials may vary. For example, mineral wool may perform well in a humid environment but less so in one heavily contaminated with mold spores. Similarly, sheep's wool insulation, while resistant to mold, is highly sensitive to liquid water and has a higher heat transfer coefficient.

Considering all factors for "niche" thermal insulation materials, it is concluded that, regardless of the raw material's nature, antifungal treatment and a proper installation technique are necessary. The antifungal treatment ensures the minimization of microorganism development and, consequently, a reduction in the negative impact on air quality and public health. Similarly, the use of a properly designed installation method would limit the transfer of air and moisture through the thermal insulation layer, assuring the longevity and effectiveness of the insulation. Proper installation techniques, adapted to the specific characteristics and vulnerabilities of each material, can significantly enhance the material's resistance to environmental stressors, including liquid water, air moisture and thermal cycling. This approach not only maximizes the thermal performance of the insulation but also its durability, contributing to the overall energy efficiency and indoor comfort of buildings. Furthermore, by ensuring that these materials are less susceptible to mold growth, the risk of structural damage and the deterioration of indoor environmental quality over time are greatly reduced. This approach of material selection, correlated with the building design, antifungal treatment, and correct installation practices, forms a comprehensive strategy for improving building sustainability and occupant health, aligning with the broader goals of reducing energy consumption and minimizing the environmental footprint of construction practices.

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