Use of Hemp Waste for the Development of Mycelium-grown Matrix Biocomposites: A Concise Bibliographic Review

Sivasubramanian Palanisamy,[a,*] Thulasi Mani Murugesan,[b] Murugesan Palaniappan,[c] Carlo Santulli,[d,*] and Nadir Ayrilmis [e]

Mycelium from fungi can serve as the matrix or as a self-grown binder in a biocomposite. The reinforcing component may consist of various combinations of agro-based waste in short fiber or powder form. The complexity of their development is linked not only to the selection of the substrate, but also to the growth conditions of the mycelial material and its consolidation in a final form by the temperature increase that takes place. These materials have initially been proposed as a replacement for polystyrene foams, and the characterization is concentrated on compression performance and acoustic and thermal insulation properties. The present review concentrates on substrates that originated from the large productive system based on hemp (shives or hurds, waste fibers, and mats). Attention is paid to the performance obtained and to the amount of waste that is possibly employed to serve as the substrate.

DOI: 10.15376/biores.18.4.Palanisamy

Keywords: Bio-blocks; Agricultural substrates; Polystyrene foam replacement; Natural fibers; Straw; Sawdust

Contact information: a: Department of Mechanical Engineering, P T R College of Engineering & Technology, Thanapandian Nagar, Madurai – Tirumangalam Road, Madurai, 625008, Tamilnadu, India; b: Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada; c: Department of Mechanical Engineering, College of Engineering, Imam Mohammad Ibn Saud Islamic University, Riyadh 11432, Kingdom of Saudi Arabia; d: School of Science and Technology, Università di Camerino, Camerino, Italy; e: Department of Wood Mechanics and Technology, Forestry Faculty, Istanbul University-Cerrahpasa, Bahcekoy, Sariyer, 34473, Istanbul, Turkey
** Corresponding authors: sivaresearch948@gmail.com; carlo.santulli@unicam.it*

INTRODUCTION

The reticular assemblies formed by the mycelium, which is fungi's root-like vegetative structure, consist of thread-like hyphae. They develop until they are heated to block any further change in shape. They have been increasingly investigated as the replacement for some types of plastic materials, in particular polystyrene foam (Abhijith *et al.* 2018). The substrate on which mycelium develops is formed by lignocellulosic biomass, often waste or by-product of other industrial sectors. In this way, the matrix is composed and bound together by the mycelium growth. The process for the creation of the composite includes the collection, grinding, and sterilization of the biomass. This is followed by inoculation, incubation at temperatures between 23 and 28 °C and at a humidity content of 50 to 70%, and finally drying at temperatures in the order of 70 °C, which stops development and gives the final geometry to the composite (Elsacker *et al.* 2019).

The described procedure makes it possible to establish a new class of composite materials, which is prevalent, yet not exclusive, and of interest in the construction industry (Javadian *et al.* 2020). Additionally, there have been suggestions for various applications of these bio-blocks, which would depend on their growth characteristics after inoculation and to the temperature (around 70 to 90 °C) and time of the "baking" process that ends the mycelial growth process (Joshi *et al.* 2020). Of course, amongst the many factors that control the self-growing of the material, is also the selection of the substrate and that of the fungal species to allow the maximum effectiveness of the production (Islam *et al.* 2017). A number of factors do influence the mechanical properties of the obtained materials: first the nature of the substrate used for growth, then the structure of the mycelium matrix obtained, including architecture of hyphal network, cell wall structure, and growth kinetics and the substrate-matrix adhesion characteristics (Jones *et al.* 2017).

One main question is whether it is feasible to dispose of general and mixed lignocellulosic waste by employing it as the substrate for mycelium growth. However, when trying a comparison with polystyrene foams, the density obtained by mycelium foams does not come down to less than 50 kg/m^3, with compression strength not exceeding 20 kPa and an even lower flexural strength (Angelova *et al.* 2021). The above properties suggest that, given the difficulty to further reduce the density, the need to achieve higher compression properties raises interest in other industries, such as footwear. With this aim, the insertion of a natural fiber (*e.g.*, jute) fabric has been proposed (Silverman *et al.* 2020).

However, there are a number of possible issues, or else factors, that may lead to potential success or failure of the process (Fig. 1). These have been integrated with further information, drawing from what was suggested by Sydor *et al.* (2022). In general terms, to improve the properties of the obtained foam, it appears important to be as specific as possible about the kind of biomass used in producing myco-composites.

The Role of Hemp in Myco-composites

Hemp (*Cannabis sativa*) is at the core of an important productive system, whose products span from food (oil, seeds, flour *etc.*) to non-food (textiles, mats, ropes, bricks, bio-fuel, phytoremediation, *etc*.) (Rheay *et al.* 2021). However, to improve the competitiveness of the industry based on this crop, it needs to be inserted into a circular economy philosophy. Attention must be paid to the use of waste biomass generated in the various productions and thereby potentially reducing the carbon footprint of this production (Scrucca *et al.* 2020). The development of myco-composites based on hemp by-products can be an opportunity in this sense.

Based on the above evidence, this review concentrates on the use of hemp-derived biomass (hurds, fibers, mats) on the development of myco-composites, and the range of properties obtained in this case. Figure 2 reports the different types of hemp-derived materials used in the literature to serve as the mycelium matrix bonding. These can all be waste or by-products of the industrial system based on this plant. Hemp has attracted considerable interest in the field of composites and is therefore widely treated in the literature, including recent reviews, such as that of Müssig *et al.* (2020). Utilization of the waste from hemp production system is also of interest, which includes the possible re-use of hemp hurds in the field of composites, combining it with pottery clay (Scardecchia *et al*. (2020), or more in general with concrete, considering that hurds constitute 70% of the whole material weight obtained from hemp system (Barbhuiya and Das 2022). It needs also to be noticed that hemp by-products are particularly adapted to binding into structures aimed for the construction industry, such as hempcrete, which is constituted by hemp shives and binder. This is another reference for myco-composites, other than the usual one with polystyrene foams (Demir and Doğan 2020).

Another possible by-product from hemp, which is usually discarded in industrial processing, is hemp pith. This relatively small part of the stem has appeared promising for acoustic properties and was used as a substrate for mycelium growth by Pelletier *et al.* (2013). Various combinations including among other materials, sorghum straw, flax shive, kenaf pith, cotton, were considered.

The lack of definition of the amount of mycelial growth obtained appears to have limited interest in such work, though the comparison indicated that, exposed to an A-weighted road noise, a 100% substrate in hemp pith offered an attenuation of around 7 dB with respect to a ceiling tile.

A further work exploiting hemp pith together with cotton ginning waste with different fiber-fungal strain combinations was performed by adding fiber fabric on the surface, therefore not pertaining, in the stricter sense, to pure myco-composites (Ziegler *et al.* 2016). This offered a maximum value of 1.06 GPa for compression strength, which was therefore superior to Styrofoam, though at the expense of around 350% water absorption. It has been suggested that hemp by-products would be among the possible candidates to serve as semi-structural myco-composite boards.

In light of the versatility of their properties, they were included in the database recently provided with this aim by Shen *et al.* (2023). This is also demonstrated by other investigations that suggest the use of hemp hurds in myco-composites as a wood replacement material. In the case of Bajwa *et al*. (2017), the enhancement of the resistance to termite attack was offered in hemp pith grown mycelium inoculated by *Trametes versicolor* by coating the board using guayule resin.

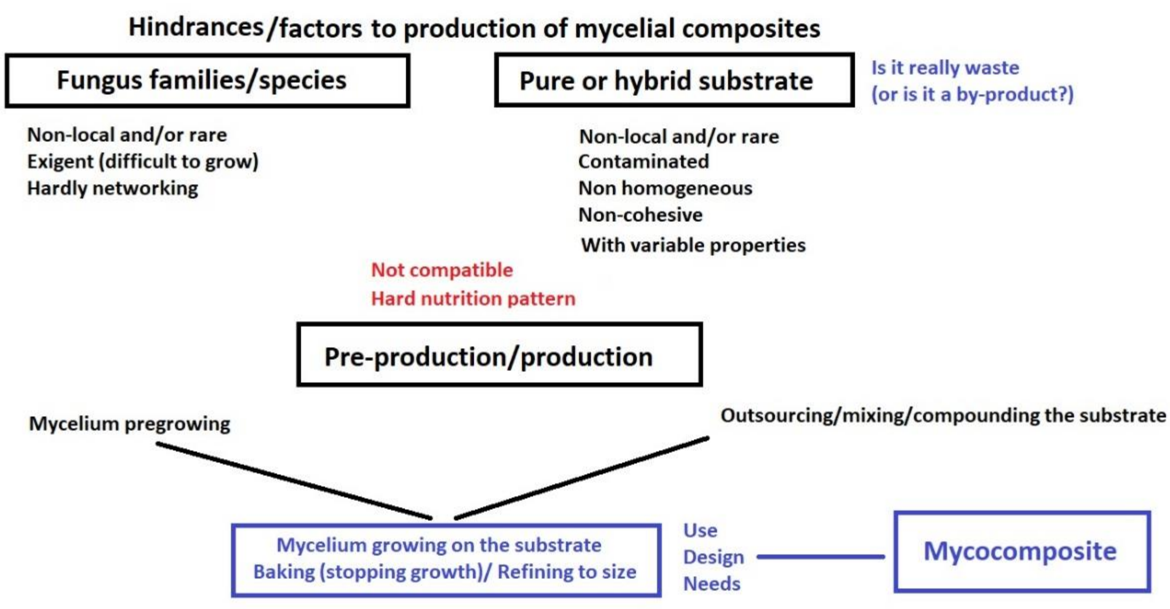

Fig. 1. Factors affecting the manufacture and use of mycelium-based composites

Fig. 2. Hemp by-products experimented as mycelium growth substrates

Hemp Hurds and Other Byproducts for Manufacturing of Myco-composites

The substrate, which is bonded with the mycelial material, would better undergo chemical characterization, so that at least the relevant lignin, cellulose, and hemicellulose content is measured. A large number of substrates have been applied over the last 15 years for mycelium growth, and this section is aimed at comparing their performance over the production of composites. To attempt a classification of the different substrates, they can be divided among prevalently ligneous (wood-like ones), ligno-cellulosic (based on those plant fibers that contain also some lignin), and cellulosic (*e.g*., from paper or straw) substrates. In some studies, a blend of different biomass materials has been used as the substrate. Specifically, hemp hurds have been reported as amongst the first waste sources, namely coming from the textile industry, that have been researched for mycelial growth using a *Pleurotus ostreatus* strain. Hemp hurds were compared with a number of other substrates, coming from other industrial sectors, such as sawdust of deciduous trees, wheat, and rye straw. The combination of hemp hurds and wheat straw offered the best results in terms of yield, reaching 69 g of *Pleurotus ostreatus* over 100 g of substrate (Sobieralski *et al.* 2011). A more organic study on eight fungi species and a similar variety of waste indicated that *Flammulina velutipes* offered the highest mycelial growth when coupled with a bare hemp hurds substrate, yet this did not lead to further investigations on the production of myco-composites, as from the explored literature (Siwuulski *et al.* 2010).

As from the data reported by Sydor *et al.* (2022), the most popular substrates in the production of mycocomposites are pine wood or undefined wood, cotton fibers, wheat bran or straw, or cellulose fibers. Hemp fibers, hurds, or mats do pertain to ligno-cellulosic biomass. Despite some variability that can be encountered among the three by-products, they always contain some amount of lignin (no more than 10%), though their main component is polysaccharidic (cellulose, hemicellulose).

Myco-composites with hemp shives substrate achieved a compression strength of 235 kPa, fast biodegradability in 12 weeks, as compatible with composting standards, yet water absorption peaked at 1000% (Loris *et al.* 2022). Another study incorporating hemp shives substrate in a *Trametes versicolor* mycelium resulted in a mycelial growth of 0.8:1, a compression strength of 190 to 200 kPa, yet an increase in stability and comparatively reduced water absorption, between 600 and 880% (Irbe *et al.* 2022). These findings, which demonstrate a very high water absorption tendency, have suggested a need for more specific studies on myco-composites having a substrate composed of biomass formed by hemp hurds and a species growing as an infesting plant in a lake environment, *Lagarosiphon* *major*, which is a typical infesting plant from internal waters (Pittau *et al.* 2022). Hemp myco-composites absorbed up to 145 g/m^2 of water for tests at relative humidity between 50 and 80%, and a water absorption of 48 kg/m^2 was measured, in both cases after 12 hours. In both cases, this was around 4 to 5 times higher than the lake plant, which was attributed to the presence of a much more diffuse and effective capillary network in hemp hurds.

Biodegradation after 12 weeks was more precisely assessed in hemp hurds myco-composites by Zimele *et al.* (2020), again with *Trametes versicolor*. It was clarified that over 70% of the mass had been lost at that moment and the compression strength obtained reached 360 ± 50 kPa, with 160 ± 20 kPa flexural strength and a density of 134 kg/m^3. Compostability was not considered as the only option for the disposal of mycocomposites grown on hemp hurds, though. A recent study on packaging materials based on this substrate suggested that at end-of-life it might serve as a precursor for a jet fuel using a one-pot ionic liquid technology (Choi *et al.* 2023).

Though hurds represent the most popular substrate for mycelial growth among hemp by-products, other options were also explored, also with comparative studies. The previously mentioned study by Elsacker *et al.* (2019), again with *Trametes versicolor*, suggested the compared use of hemp waste in different formats, namely hurds, compressed or not, in the dimension range of 5 to 25 mm, and chopped fibers, smaller than 5 mm. In no case did the dry density exceed 100 kg/m^3 and the compression Young's modulus was revealed to be in the region of 1 MPa. Water absorption in these composites was in the range of 2 to 3.5 kg/m^2. Around the same interval was also observed the competing flax or straw biomass as a substrate.

Moreover, the relation between the types of fungi for mycelium growth and the relevant substrate needs to be investigated. *Trametes versicolor* appears, as from the literature, to be among the most suitable for the use of hemp biomass. However, a further recent study did investigate the application of edible fungi, namely *Pleurotus ostreatus*, on hemp hurds for the production of myco-composites with a relatively low incubation time of 16 days, though the mechanical properties of the obtained boards were not reported (Reiss II 2022). It is also noteworthy that the same species of edible fungi has been used in a solid-state fermentation process of hemp biomass to enhance its nutritional profile to provide a highly proteinaceous food for animals, which suggests a high level of compatibility between hemp cellulosic products and *Pleurotus ostreatus* (Eliopoulos *et al.* 2022).

Another possibility was to combine hemp with other cellulosic materials, to serve as a hybrid substrate for mycelium. In particular, a study performed by Elsacker *et al.* (2021) blended 5 to 25 mm hemp hurds with bacterial cellulose in a mycelium (*Trametes versicolor*) matrix. The boards were densified at 70 and then at 200 °C. Mechanical testing was performed after a curing process of 4 weeks at 21 °C and 65% relative humidity. In particular, tensile (largely varying values, with maximum at 76.4 MPa), flexural (average value 2.94 MPa), and internal bond testing (average value at 54 Pa) was carried out. A different type of hybridization using hemp hurds as the support for *Pleurotus ostreatus* growth in myco-composites was performed by the addition of laterite by Etinosa *et al*. (2023). This proved effective up to 70 wt.%, to try to offer a higher compression strength, up to 800 kPa, though losing in the ductility of the material.

The comparison of different forms of hemp by-products (hurds, loose fibers, non-woven mats) together with two fungi species, *Coriolus versicolor* and *Pleurotus ostreatus*, for mycelium growth was developed by Lelivelt *et al.* (2015). The most promising results were obtained using hemp mat with *Coriolus versicolor*, which resulted in the highest level of densification of the foam during testing, achieving a level of compressive strength between 24 and 93 kPa with a density between 170 and 250 kg/m^3 (Lelivelt 2015).

Despite the aforementioned difficulties in using mixed agrowaste for the production of mycocomposites, on the other side, hybrid substrates would also be worthy of consideration in view of the maximization of profits and yields as regards the biorefinery concept, using widely available agrowaste, such as straw (Jones *et al.* 2020).

An example of a hybrid substrate that has been attempted in combination with hemp hurds is wheat bran (Sisti *et al.* 2021). Hemp shives presented dimension ranges of 10 to 15 mm length, 3 to 6 mm width, and 1 to 1.5 mm thickness, whilst wheat bran was a waste from pasta production, in the form of flakes with an approximate volume of 1 mm^3. In the above study, for the first time, superhydrophobic properties of mycelium-based materials have been investigated, with a contact angle of 131° for a 20 wt% wheat bran content. However, mechanical properties started decreasing from the addition to hemp of more than 10 wt% wheat bran, though the values were significantly high, 820 MPa compression strength for 75% deformation, and 100 MPa flexural strength for 70% deformation. The introduction of wheat bran in combination with hemp hurds does appear promising, though the advantage might be variable, due to the wide dispersion of the particles' aspect ratio (Rahman *et al.* 2021).

To try to develop usable products, for example acoustic boards based on myco-composites, sometimes a generic approach is used, mixing the various by-products previously indicated of the hemp system. This was the case for pollutant absorbing panels, where hemp-based myco-composites (204 mg/kg) proved superior with respect to rice straw (169 mg/kg) and lacquer tree wood chip (59 mg/kg) ones (Lee and Choi 2021). These results are promising as a part of a trend in trying to introduce myco-composites grown from hemp hurds in the actual building paneling as complement for plywood rather than a self-supported structure, such as reported by Almpani-Lekka *et al.* (2021), on a hemp hurds myco-composite grown on *Fomes fomentarius.* A more structural application has been proposed in the creation of hemp hurds myco-composites based on wood veneer with an inoculation of *Ganoderma lucidum*, and prepared in comparison with the bare myco-composite not including wood veneer molded to a density of 145 kg/m^2 (Őzdemir *et al.* 2022). Tensile, flexural, pull-out, and compression tests have been performed. In particular, the coverage with the low-density veneer brought some improvement in the flexural strength from 170 to 190 kPa, while it offered 30.6 MPa of tensile strength, and 360 kPa of pull-out strength. In contrast, compression strength was in the order of 1.2 MPa.

CONCLUSIONS

The so-called myco-composites, where lignocellulosic material adhere together by the insertion of an adapted networking material provided by the mycelium hyphae, has shown increasing success, as demonstrated by the exponentially growing number of publications over the last years. This can be attributed to the large availability of both the matrix and the filler material, particularly enhanced by the need to dispose of agrowaste, which in some cases presents both a scarce adaptability to integration into compost and is even less suitable to be applied as energy recovery by carbonization. A production system that offers the possibility of a variety of ligno-cellulosic waste is hemp. In particular, hurds or shives, as well as fibre waste and more generally hemp textile scraps have been used in a number of occasions to serve as the support for the production of myco-composites with obvious limitations due to their high water absorption and capillarity. However, they are able to offer successful combinations with other biomass, such as wheat straw, and have proved successful with inoculations of different fungi, such as *Trametes versicolor* and *Pleurotus ostreatus*. Future challenges are in the control of the biomass properties in terms of absence of contamination and of limited variability of the properties, which might also reduce the required incubation times, considering that hemp yielding as a substrate appeared generally among the highest for biomass used in myco-composites production.

Data Availability Statement

Data available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES CITED

Abhijith, R., Ashok, A., and Rejeesh, C. R. (2018). “Sustainable packaging applications from mycelium to substitute polystyrene: A review,” *Materials Today: Proceedings*, Elsevier, 5(1), 2139-2145. DOI: 10.1016/j.matpr.2017.09.211

Almpani-Lekka, D., Pfeiffer, S., Schmidts, C., and Seo, S. I. (2021). "A review on architecture with fungal biomaterials: The desired and the feasible," *Fungal Biology and Biotechnology* 8(1), 17. DOI: 10.1186/s40694-021-00124-5

Angelova, G. V, Brazkova, M. S., and Krastanov, A. I. (2021). “Renewable mycelium based composite–sustainable approach for lignocellulose waste recovery and alternative to synthetic materials–A review,” *Zeitschrift für Naturforschung C*, De Gruyter 76(11–12), 431-442. DOI: 10.1515/znc-2021-0040

Bajwa, D. S., Holt, G. A., Bajwa, S. G., Duke, S. E., and McIntyre, G. (2017). "Enhancement of termite (*Reticulitermes flavipes* L.) resistance in mycelium reinforced biofiber-composites." *Industrial Crops and Products* 107, 420-426. DOI: 10.1016/j.indcrop.2017.06.032.

Barbhuiya, S., and Das, B. B. (2022). "A comprehensive review on the use of hemp in concrete," *Construction and Building Materials* 341, article 127857. DOI: 10.1016/j.conbuildmat.2022.127857

Choi, J., Rodriguez, A., Simmons, B. A., and Gladden, J. M. (2023). "Valorization of hemp-based packaging waste with one-pot ionic liquid technology," *Molecules* 28(3), article 1427. DOI: 10.3390/molecules28031427

Demir, İ., and Doğan, C. (2020). "Physical and mechanical properties of hempcrete," *The Open Waste Management Journal* 13(1), 26-34. DOI: 10.2174/1874312902014010026

Eliopoulos, C., Markou, G., Chorianopoulos, N., Haroutounian, S. A., and Arapoglou, D. (2022). "Preliminary research concerning the enrichment of industrial hemp extract residues *via* solid state fermentation with *Pleurotus ostreatus*," *Applied Sciences* 12(5), 2376. DOI: 10.3390/app12052376

Elsacker, E., Vandelook, S., Brancart, J., Peeters, E., and De Laet, L. (2019). “Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates," *PLoS One,* Public Library of Science San Francisco, CA USA, 14(7), e0213954. DOI: 10.1371/journal.pone.0213954

Elsacker, E., Vandelook, S., Damsin, B., Van Wylick, A., Peeters, E., and De Laet, L. (2021). "Mechanical characteristics of bacterial cellulose-reinforced mycelium composite materials," *Fungal Biology and Biotechnology* 8(1), 1-14. DOI: 10.1186/s40694-021-00125-4

Etinosa, P. O., Salifu, A. A., Azeko, S. T., Obayemi, J. D., Onche, E. O., Aina, T., and Soboyejo, W. O. (2023). "Self-organized mycelium biocomposites: Effects of geometry and laterite composition on compressive behavior," *Journal of the Mechanical Behavior of Biomedical Materials* 142, article 105831. DOI: 10.1016/j.jmbbm.2023.105831

Irbe, I., Loris, G. D., Filipova, I., Andze, L., and Skute, M. (2022). "Characterization of self-growing biomaterials made of fungal mycelium and various lignocellulose-containing ingredients," *Materials* 15(21), article 7608. DOI: 10.3390/ma15217608.

Islam, M. R., Tudryn, G., Bucinell, R., Schadler, L., and Picu, R. C. (2017). "Morphology and mechanics of fungal mycelium," *Sci. Reports* 7(1), article 13070. DOI: 10.1038/s41598-017-13295-2

Javadian, A., Le Ferrand, H., Hebel, D. E., and Saeidi, N. (2020). "Application of mycelium-bound composite materials in construction industry: A short review," *SOJ Materials Science & Engineering* 7(2), 1-9. DOI: 10.3929/ethz-b-000543782

Jones, M., Huynh, T., Dekiwadia, C., Daver, F., and John, S. (2017). "Mycelium composites: A review of engineering characteristics and growth kinetics," *Journal of Bionanoscience* 11(4), 241-257. DOI: 10.1166/jbns.2017.1440

Jones, M., Mautner, A., Luenco, S., Bismarck, A., and John, S. (2020). "Engineered mycelium composite construction materials from fungal biorefineries: A critical review," *Materials & Design* 187, article 108397. DOI: 10.1016/j.matdes.2019.108397

Joshi, K., Meher, M. K., and Poluri, K. M. (2020). "Fabrication and characterization of bioblocks from agricultural waste using fungal mycelium for renewable and sustainable applications," *ACS Applied Bio Materials* 3(4), 1884-1892. DOI: 10.1021/acsabm.9b01047

Lee, T., and Choi, J. (2021). "Mycelium-composite panels for atmospheric particulate matter adsorption," *Results in Materials* 11, article 100208. DOI: 10.1016/j.rinma.2021.100208

Lelivelt, R. J. J. (2015). *The Mechanical Possibilities of Mycelium Materials*, Master Thesis, Eindhoven University of Technology (TU/e), 682.

Lelivelt, R. J. J., Lindner, G., Teuffel, P., and Lamers, H. (2015). "The production process and compressive strength of mycelium-based materials," in: *First International Conference on Bio-based Building Materials.* 22-25 June 2015, Clermont-Ferrand, France (pp. 1-6).

Loris, G. D., Irbe, I., Skute, M., Filipova, I., Andze, L., and Verovkins, A. (2022). "Hemp shives mycelium composites - An alternative material for traditionally used plastic packaging," in: *Materials Science Forum*, Trans Tech Publ, 126-138. DOI: 10.4028/p-yl4pa1

Muiruri, J. K., Chuan Yeo, J. C., Zhu, Q., Ye, E., Loh, X. J., and Li, Z. (2023). "Sustainable mycelium-bound biocomposites: Design strategies, materials properties, and emerging applications," *ACS Sustainable Chem. & Eng.* 11(18), 6801-6821. DOI:

10.1021/acssuschemeng.3c00831
Müssig, J., Amaducci, S., Bourmaud, A., Beaugrand, J., and Shah, D. U. (2020). "Transdisciplinary top-down review of hemp fibre composites: From an advanced product design to crop variety selection," *Composites Part C: Open Access* 2, article 100010. DOI: 10.1016/j.jcomc.2020.100010
Özdemir, E., Saeidi, N., Javadian, A., Rossi, A., Nolte, N., Ren, S., and Eversmann, P. (2022). "Wood-veneer-reinforced mycelium composites for sustainable building components," *Biomimetics* 7(2), 39. DOI: 10.3390/biomimetics7020039
Pelletier, M. G., Holt, G. A., Wanjura, J. D., Bayer, E., and McIntyre, G. (2013). "An evaluation study of mycelium based acoustic absorbers grown on agricultural by-product substrates," *Industrial Crops and Products* 51, 480-485. DOI: 10.1016/j.indcrop.2013.09.008
Pittau, F., Carcassi, O. G., Servalli, M., Pellegrini, S., and Claude, S. (2022, September). "Hygrothermal characterization of bio-based thermal insulation made of fibres from invasive alien lake plants bounded with mycelium," in: *IOP Conference Series: Earth and Environmental Science* (Vol. 1078, No. 1, p. 012069). IOP Publishing.
Rahman, A., Fehrenbach, J., Ulven, C., Simsek, S., and Hossain, K. (2021). "Utilization of wheat-bran cellulosic fibers as reinforcement in bio-based polypropylene composite," *Industrial Crops and Products* 172, article 114028. DOI: 10.1016/j.indcrop.2021.114028
Reiss II, M. W. (2022). *Pleurotus ostreatus Production on Cannabis sativa L.(Industrial Hemp) Residues for Edible Mushrooms and Mycelium-based Composites,* Ph.D. Dissertation, Virginia Tech.
Rheay, H. T., Omondi, E. C., and Brewer, C. E. (2021). "Potential of hemp (*Cannabis sativa* L.) for paired phytoremediation and bioenergy production," *GCB Bioenergy* 13(4), 525-536. DOI: 10.1111/gcbb.12782
Scardecchia, S., Vita, A., Santulli, C., and Forcellese, A. (2020). "A material proposed for re-use of hemp shives as a waste from fiber production," *Materials Today: Proceedings* 31, S213-S216. DOI: 10.1016/j.matpr.2019.11.063
Scrucca, F., Ingrao, C., Maalouf, C., Moussa, T., Polidori, G., Messineo, A., and Asdrubali, F. (2020). "Energy and carbon footprint assessment of production of hemp hurds for application in buildings," *Environ. Impact Assess. Rev.* 84, article 106417. DOI: 10.1016/j.eiar.2020.106417
Shen, S. C., Lee, N. A., Lockett, W. J., Acuil, A. D., Gazdus, H. B., Spitzer, B. N., and Buehler, M. J. (2023). "Robust myco-composites as a platform for versatile hybrid-living structural materials," *arXiv preprint arXiv:*2305, 12151. DOI: 10.48550/arXiv.2305.12151
Silverman, J., Cao, H., and Cobb, K. (2020). "Development of mushroom mycelium composites for footwear products," *Clothing and Textiles Res. J.* 38(2), 119-133. DOI: 10.1177/0887302X198900
Sisti, L., Gioia, C., Totaro, G., Verstichel, S., Cartabia, M., Camere, S., and Celli, A. (2021). "Valorization of wheat bran agro-industrial byproduct as an upgrading filler for mycelium-based composite materials," *Indust. Crops Prod.* 170, article 113742. DOI: 10.1016/j.indcrop.2021.113742
Siwulski, M., Sobieralski, K., and Mańkowski, J. (2010). "Comparison of mycelium growth of selected species of cultivated mushrooms on textile industry wastes," *Acta Scientiarum Polonorum Hortorum Cultus* 9(3), 37-43.
Sobieralski, K., Siwulski, M., Sas-Golak, I., Mańkowski, J., and Kotlińska, T. (2011).

"Mycelium growth and yield of wild strains of (Jacq.: Fr.) Quel. cultivated on waste materials from the textile industry," *Folia Horticulturae* 23(1), 67-71. DOI: 10.2478/v10245-011-0011-8

Sydor, M., Cofta, G., Doczekalska, B., and Bonenberg, A. (2022). "Fungi in mycelium-based composites: usage and recommendations," *Materials* 15(18), article 6283. DOI: 10.3390/ma15186283

Ziegler, A. R., Bajwa, S. G., Holt, G. A., McIntyre, G., and Bajwa, D. S. (2016). "Evaluation of physico-mechanical properties of mycelium reinforced green biocomposites made from cellulosic fibers," *Applied Engineering in Agriculture* 32(6), 931-938. DOI: 10.13031/aea.32.11830

Zimele, Z., Irbe, I., Grinins, J., Bikovens, O., Verovkins, A., and Bajare, D. (2020). "Novel mycelium-based biocomposites (Mbb) as building materials," *Journal of Renewable Material* 8(9), 1067-1076. DOI: 10.32604/jrm.2020.09646

Article submitted: August 28, 2023; Peer review completed: September 30, 2023; Revised version received: October 19, 2023; Accepted: October 20, 2023; Published: October 31, 2023.

DOI: 10.15376/biores.18.4.Palanisamy