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AN OVERVIEW ON MICROORGANISMS DERIVED BIO-MATERIALS

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Abstract

Petrochemical-based packaging materials represent a billion dollar industry that makes possible modern innovations in sustainable packaging design, but with severe footprint on the environment. Currently, polystyrene products take over 30% of worldwide landfill space which represents a real issue as sustainable disposal methods must be pursued, given the fact that polystyrene products are incredibly hard to recycle and biodegrade (approximately 500 years for styrofoam to organically degrade). The paper presents main biotechnological advances regarding mycelium based bio-materials used as sources of renewable protective packaging materials, structural bio-composites, thermal insulation materials, packaging materials, decorative objects etc. Biotechnological processes successfully explore the great potential of Basidiomycetes strains (E.g.: Pleurotus djamor, Pleurotus eryngii, Pleurotus ostreatus,Grifola frondosa, Ganoderma lucidum, Ganoderma oregonense, Lentinula edodes, Agrocybe aegerita, Coprinus comatus etc.) in obtaining mycelium-based novel bio-materials.

***Key words**: fungi, basidiomycetes, composite materials, agricultural biomass.*

INTRODUCTION

Petrochemical-based packaging materials represent a billion dollar industry that makes possible modern innovations in sustainable packaging design. Even plastic packaging has obvious advantages, such as price/kg, manufacturing speed, physical-mechanical properties etc., their production involve high consumption of fossil fuels, energy and water, multiple complex manufacturing stages, each of them with severe footprint on the environment (Kremer, 2003). Disposal of such materials into the environment contributes to an array of environmental problems, affecting humans' health, soil and marine habitats degradation, ground water contamination, long-term pollution (Maachia et al., 2005). Currently, polystyrene products take over 30% of worldwide landfill space which represents a real issue as sustainable disposal methods must be pursued, given the fact that polystyrene products are incredibly hard to recycle and biodegrade (approximately 500 years for Styrofoam to organically degrade). Current researches focus on obtaining alternative packaging materials by development of environmentally safe and cost-efficient process for preparation of mycological materials for packaging as green alternative to highly polluting plastics. The production of 1 m^3 of polystyrene consumes 4,667 mega Joules (MJ) of energy and release into the atmosphere 462 kg of CO_2 while the production of 1m^3 of mycelium derived bio-material uses 652 MJ and releases 31 kg of CO_2.

Regarding the novelty of this research field, both scientific and technological future objectives are to be achieved with the sustained effort of multidisciplinary industries, which may include both SMEs and research organizations, representing the whole value chain, from producers and suppliers of agricultural and textile wastes, biotechnology processors to packaging producers.

CONTEXT

Robust, low-cost, non-toxic manufacturing processes represent major factors driving future markets and demand for bio-based materials in the European Union. According to EPA (United States Environmental Protection Agency) data provided by Ecovative, the pioneer of mycelium-based bio-materials, plastics - especially plastics like EPS (expanded polystyrene) - take up 25 percent of US landfills by volume. The environmentally safe, fire resistant, VOC free, and 100% sustainable and compostable mycelium materials have a wide range of applicability: the packaging industry will be more competitive by replacing petroleum-derived polymers with sustainable and fully biodegradable/compostable materials.

Innovative biotechnological processing for transforming and improving exploitation of waste and by-products from agriculture, fruit and vegetable processing industry, plastic and textile industries, will reduce the environmental impact of wastes, will enhance the sustainable management of organic wastes as they can be used as feedstock for value-added bio-based materials. Sustainable packaging development addresses economic, environmental and social objectives, which are dynamically interconnected.

Bio-materials obtained by growth of fungi on industrial waste have generated tremendous interest worldwide due to the obvious benefits: the transformation of huge volumes of waste with low consumption of energy, water and chemicals, into valuable products with applications in the most diverse fields: packaging materials replacing polystyrene plastics (Heredia-Guerrero et al., 2016), constructions, architectural design, interior decorations, garments etc., economic, social and environmental benefits. However, the technology is still incipient due to the low reproducibility of the materials created, the final properties strongly depending on the variable composition of the waste, the type of strain used, the growth and post-treatment conditions, the design and the geometric shape of the enclosure which occurs in mycelium growth.

The market for plastic packaging (polystyrene, polyethylene terephthalate, polyethylene, polypropylene, polyvinyl chloride, polyamide, polyurethane and lactic acid) was estimated at \$189.43 billion in 2015 and is expected to reach \$262.68 billion 2021, at an RCAC (annual composite growth rate) of 5.71%. The annual consumption of rigid packaging is 30€ billion in the EU, while flexible packaging amounts to about 10€ billion. About 63% of all EU consumer goods are marketed in plastic packaging. The global market for biodegradable paper packaging materials are estimated to grow to an RCAC of nearly 11% between 2017 and 2021, bioplastic packaging materials dominating the global market, accounting for 54% of the market share in 2016 (Technavio report).

MICROBIAL STRAINS AND PROCESSES

Filamentous fungi are the most effective and competitive microorganisms used to produce mycelium-based materials due to their physiological, enzymatic and biochemical properties. They possess versatile and high secretory capabilities, good tolerance to high osmotic pressure conditions, exponential growth of biomass, large amounts of hydrolytic enzymes excreted at the top of their hyphae, allowing the penetration and degradation of nearly all solid substrates. The use of filamenttous fungi properties to develop mycelia networks lead to the creation of safe and inert, light, strong and durable, fire - resistant and insulating materials (insulation value of R-3 or R-4) (Figure 1) that can successfully replace materials made of plastic (polystyrene) (Vilela et al., 2014).

(Source: www.smithsonianmag.com)

(Source: www.equipmentworld.com)

Figure 1. Mycelium based insulation materials

They can be used for a wide range of applications, including insulation, packing materials, building blocks, acoustic boards, sandwich panels (Figure 2), decorative products (Figure 3) (Johansson et al., 2012).

Figure 2. Mycelium based
(Source: www.architectmagazine.com)

Figure 3. Mycelium based decorative products
(Source: www.wired.com)

Bio-composites based on fungal mycelium are considered to be one of the future generations of renewable materials due to their obvious advantages: rapid growth (approximately 10-14 days) on almost all types of waste transformed into valuable products, organic composition (cellulose, chitin, fats, carbohydrates, various nitrogen species, vitamins and minerals), low costs and broad availability (Vega et al., 2012). More than that, the production of packaging material from mycelia and waste uses 12% of the energy normally required in the manufacture of traditional plastic packaging and reduce carbon emissions by up to 90%. However, the technology is on baby footsteps due to the low reproducibility of the materials created by using biological organisms especially on wastes having variable composition. Also, the most challenging problem remains the final properties of the mycelium materials which strongly depends on the type of fungi and wastes used, the growing and post-treatment conditions, the design and geometrical shape of enclosure (Figure 4): the material could be frangible and brittle when is too much desiccated (Allan, 2017), fracturing occurring at the boundaries between areas of mycelium growth and undigested wastes, and chemical composition and final morphologies are highly different from substrate to substrate (Mazur, 2017; Travaglini et al., 2017).

Figure 4. Geometrical formulations of mycelium based structures
(Source: www.builderonline.com)

Fungal mycelium is mainly composed of natural polymers (chitin, cellulose, proteins, etc.) (Figure 5) which due to its unique structure and composition, correlated with enzymatic activity able to hydrolyze a wide variety of organic substrates, can be exploited with success in producing bio-materials (Vega et al., 2012).

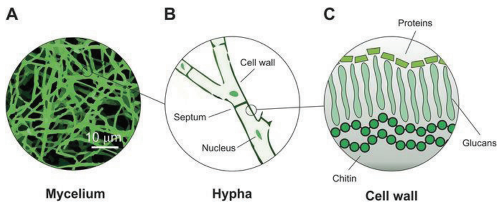

Figure 5. Representation of mycelium physiology
(Source: Haneef et al, 2017)

Patents US 2011/0306107 A1 and US8283153 B2 describe the methods to prepare mycelium from *Pleurotus djamor, Pleurotus eryngii, Pleurotus ostreatus, Pleurotus ostreatus var. columbines, Grifola frondosa, Ganoderma lucidum, Ganoderma oregonense, Lentinula edodes, Agrocybe aegerita or Coprinus* *comatus*. Even though the mycelium prepared according to above mentioned show fast growth ability, the provided methods are suitable mainly for the development of biodegradable packaging from plastics and plastic foams. Muhammad Haneef described the use of white rot fungi (*Ganoderma lucidum* and *Pleurotus ostreatus*) for production of mycelium-based fibrous films, but pure amorphous cellulose and a mixture of cellulose and PDB are used as nutritive substrates to obtain a high growth of the mycelium materials and acceptable mechanical properties of the bio-films (Haneef et al., 2017). Patent US 2011/8001719 B2 provides the method of growing Basidiomycetes and Ascomycetes fungal fruiting bodies into a low density, chitinous material (Vega et al., 2012) that can replace balsa, bass, other woods, and also foam based plastics. Specific conditions and multiple stages are required to activate primordia maturation and induce fruiting of fungal primordium in the organism type. Patent US no. 5854056 discloses a process for the production of „phylum fungal pulp" but the method is optimized for *Neurospora crassa* as the filamentous fungus that can be used in the production of paper products and textiles. Patent US 2015/0342138 provides a method for producing dehydrated mycelium which can be re-hydrated and rapidly re-formed into many different shapes, such as bricks, blocks, pellets and the like elements wherein the adhesion of the elements is achieved through re-animation of a fungal organism which grows the elements together.

However, none of the patents describes the production in a cost-effective manner of an achievable fungal consortium able to degraded wastes with variable composition, so more versatile and higher yielding fungal strains are needed to up-scale the process. Also, the know-how about specific mechanism is very limited and precludes further optimization options including directed evolution approaches for selective fine tuning of processes.

MAIN CHALENGES

Despite all efforts, the technologies for making mycelium based materials are still in incipient phases due to low reproducibility of the materials created by the use of biological organisms on waste with variable composition (Papagianni, 2004). Also, the most difficult problems remain the final properties of materials obtained by fungal mycelium, which strongly depend on the type of used fungi and waste, growth conditions, post-treatment processes, the design and geometric shape of the final enclosures where microbial growth takes places (Figure 6), which can cause several mechanical changes in the final products: chemical composition and final morphologies differ greatly with strain inoculation on various substrates.

Figure 6. 3D-printed mold for mushrooms growing (Source: www.make.land)

To improve the process, complex experimental determinations are needed, more versatile and with higher yields. Also, the know-how about the specific mechanism is very limited and hinders additional optimization options, including targeted approaches for regulating the fine selectivity of fungal mycelium growth on various organic wastes.

Patents US 2008/0145577 A1, US 2012/0315687 A1 and US 2016/0002589 A1, describe the use of agricultural waste as nutritive substrate (cotton seed hulls, coconut coir), minerals (horticultural perlite, vermiculite, diatomaceous earth), industrial waste (sawdust, waste cellulose pulp from paper mill or recycled paper, foam based products and polymers) for obtaining of mycelium-based materials. However, until now, the most challenging, not yet solved problem of waste substrate is the high heterogeneity of the mixture components with different structures which makes difficult the uniform growth of the mycelium mass, and leads to varying quality of obtained packaging materials. Another challenge is the bio-contamination with unwanted fungi and/or bacteria which could hamper the further bio-processing.

APPLICATION FIELDS AND KEY PLAYERS

The key players for bio-plastic packaging materials include Amcor Ltd., Crown Holdings Inc., Bemis Company Inc., Basf SE, Huhtamaki Oyj, Mondi, Sealed Air Corp., Sonoco Products, Saint-Gobain etc. The global production capacity of bio-plastics will increase to about 6.1 million tons in 2021, with packaging accounting for nearly 40% (1.6 million tons) of the total bio-plastics market. Trends show an increase in demand for bio-plastics in the automotive and transport sector (14%, 0.6 million tone) and the construction sector (13%, 0.5 million tons). Even if the benefits of mycelium-based materials are obvious, such as 25% reduction of waste landfills, biodegradability, there are very few companies producing such bio-composites. Ecovative Design, USA, is the leading bio-composites company engaged in research and development of ecological packaging materials (EcoCradle) (Penelope, 2012) by transforming and casting agricultural waste into the required packaging forms using mycelium. Mycological materials are used to package products made by various companies such as Ikea, Dell, Surf Organic Boards and Danielle Trofe Design to develop sustainable surfboards, lampshades and plant pots (Figure 7).

Figure 7. Ecovative Design's proprietary EcoCradle® mycelium-based materials
(Source: www.ecovative.com)

Architectural elements (garden decorations, floral foam materials), furniture and other building materials are developed by architect David Benjamin (New York, USA). Various research institutes and universities are involved in the study of mycelium-based materials: Karlsruhe Institute of Technology, ETH Zurich, University of Leeds, UK, Het Nieuwe Instituut, Netherlands, in collaboration with Vitra Design Museum, makes architectural elements. TuDelft University, Netherlands, is involved in a project aimed at the development of mycelium composite materials with different physical properties ranging from elastic to rigid, hydrophilic/hydrophobic and porous/ compact.

The markets for bio-materials include many applicative industrial sectors such as:

- Constructions sector: insulating panels, sandwich panels, bricks, acoustic tiles (Johansson et al., 2012), office furniture, furniture packaging;
- Electrical and electronic applications: packaging materials for LCD flat screens, electronic devices, telephones, IT & C components;
- Packing materials for sports, leisure and design, consumer goods;
- Outdoor and garden products: decorative materials, biodegradable flower pots (Figure 8);
- Automotive and transport sector: panels and door bars, lightweight automotive panels, machine parts packaging.

Figure 8. Mycelium based flower pots
(Source: www.danielletrofe.com)

CONCLUSIONS

This novel field proposes obtaining of bio-material that harvest the great potential of higher fungi which pose high bio-efficiency and are able to break down a wide variety of nutritive substrates, rapid hyphae grow (netting) and versatility towards cultivation parameters changes on a wide range of substrates. The potential for waste to be converted into biodegradable packaging will dominate research efforts in recent years due to their high availability, low environmental footprint, a wide range of achievable products (insulation, building blocks, acoustic boards, sandwich panels, decorative products, architectural design, decorations interior, packaging materials etc.) (Johansson et al., 2012).

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REFERENCES

Allan M., 2012. Testing and Characterization of Mycelium Composites. Mechanical Engineering, Union College, Maine.

Haneef M., Ceseracciu L., Canale C., Bayer I.S., Heredia-Guerrero J.A., Athanassiou A., 2017. Advanced Materials From Fungal Mycelium: Fabrication and Tuning of Physical Properties. Scientific Reports volume 7, Article number: 41292.

Heredia-Guerrero J.A., Athanassiou A., 2016. Non-Polysaccharide Plant Polymeric Materials. Frontiers in Materials, 15.

Johansson C., Bras J., Mondragon I., Nechita P., Plackett D., Simon P., Gregor Svetec D., Virtanen S., Baschetti M.G., Breen C., Aucejo S., 2012. Renewable Fibers and Bio-Based Materials For Packaging Applications - A Review of Recent Developments. BioResurces, Vol 7, No 2.

Kremer A., 2003. Cradle to Grave: The Life Cycle of Styrofoam®. San Francisco State University.

Maachia L., Boutefnouchet N., Bouzerna N., Chettibi H., 2005. Assessment of The Petrochemical Industry Pollution on the Skikda Bay, Algeria. International Journal of Environmental Research and Public Health 2(3-4):463-8.

Mazur R., 2015. Mechanical Properties of Sheets Comprised of Mycelium: A Paper Engineering Perspective. Thesis, Environmental Resources Engineering Department, State University of New York, College of Environmental Science and Forestry.

Papagianni M., 2004. Fungal morphology and metabolite production in submerged mycelial processes. Biotechnology Advances 22, 189–259, doi: 10.1016/j.biotechadv.2003.09.005.

Penelope Z., Zocher D., 2012. Ecovative's Breakthrough Biomaterials. Fungi Magazine 5, 51–56.

Travaglini S., Noble J., Ross P.G., Dharan C.K.H., 2013. Mycology Matrix Composites. Annual technical conference, 28th, American Society for Composites, State College, PA, in Proceedings-American Society for Composites, 1;517-535.

Vega K., Kalkum M., 2012. Chitin, chitinase responses, and invasive fungal infections. International Journal of Microbiology, 920459–920459, doi: 10.1155/2012/920459.

Vilela C., Sousa A.F., Fonseca A.C., Serra A.C., Coelho J.F.J., Freire C.S.R., Silvestre A.J.D., 2014. The quest for sustainable polyesters-insights into the future. Polymer Chemistry 5, 3119–3141, doi: 10.1039/c3py01213a.

Website:https://femaleandfungi.com/2016/03/10/replacing-petroleum-based-products-with-breakthrough-biomaterials/ (Accessed on 31-01-2018).

Website:https://ecovativedesign.com/how-it-works (Accessed on 31-01-2018).

Website:hhttp://www.scientificamerican.com/article/strange-but-true-largest-organism-is-fungus (Accessed on 31-01-2018).

Website:http://jncc.defra.gov.uk/page-5784-theme=textonly (Accessed on 30-01-2018).

Website:http://www.biofuelsdigest.com/bdigest/2016/11/30/global-bioplastics-production-to-reach-6-1-million-tons-by-2021/ (Accessed on 25-01-2018).