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Harnessing Nature An In-depth Study on the use of Biodegradable Plant-based Packaging Materials to Reduce Environmental Degradation, and Achieve Sustainability Goals

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Abstract—*The paper attempts to understand alternative options to single-use plastics and to material used in the construction industry, which are biodegradable and environment friendly. Amongst them Mycelium (the vegetative part of a fungus, which consists of a network of fine white filaments called hyphae) has emerged as a strong contender. This product is already in use in various companies and areas. Universal use of it would require reduction in costs which could be achieved by research and economies of scale.*

Research Question: *Sustainability has become an extremely important concern in the world today. Concerted effort has to be made on all fronts to combat this disaster, including even percolating down to the packaging industry. This paper attempts to analyse how the packaging industry could use natural plant material to further the cause of sustainability. Will the process be economically viable? What are the costs involved in it becoming cost effective? What would be the timespan involved in its universal usage? These and other such questions would be attempted in the course of the study.*

Keywords: *Mycelium, Greenhouse gasses, Carbon imprint, Fossil Fuels Biopolymers, Bioplastics,*

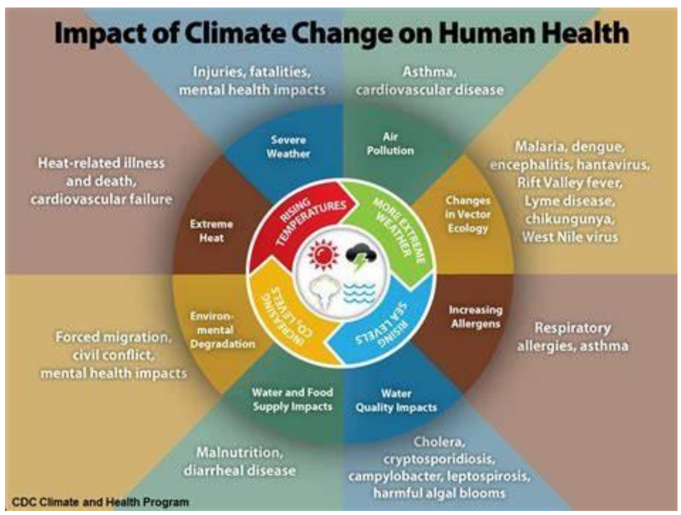
1. INTRODUCTION

Climate change in recent years has been creating havoc all over the world. This has resulted in the world trying to address issues of environmental sustainability, with the aim of leaving a healthy environment for future generations. The aim of nearly all nations of the world, irrespective of their development status, is to control the emissions of greenhouse gasses and reduce carbon imprints. The impact of the above two has resulted in an increase in global temperature, which has triggered multiple negative effects on the planet.

The rise in temperature has influenced the physical, biological, and human systems, which can be seen in the following ways:

- The disruption of the physical systems of the planet can be observed in the melting of the poles; these in turn cause glacial regression, melting of snow, flooding of rivers, coastal erosion, and sea level rising.
- In the biological systems there is death of flora and fauna in both the terrestrial and marine system. There is a simultaneous displacement of both resulting in the search of better life conditions.
- In the case of human systems, climate change affects and destroys crops and food production causing disease and death, resulting in migration of climate refugees.

All of the above cannot be considered in isolation as the impact of one is felt on the other and vice versa.



Source: Lancet Countdown

Figure 1: Effect of Climate Change on Health

Fossil fuels – coal, oil and gas - are the largest contributors to global climate change. They account for over 75% of global greenhouse gas emissions and nearly 90% of all carbon dioxide emissions (https://www.un.org/science/causes and effects of climate change). These gasses blanket the earth, trapping the sun's heat and leading to global warming, which impacts the normal balance of nature, posing many risks to human beings and all other forms of life on earth.

The many causes of emission of these gasses are:

- Generating electricity by burning fossil fuels. Most electricity across the world is still generated by burning coal, oil, or gas which produces carbon dioxide and nitrous oxide, which in turn trap the sun's heat. Presently only 29% of the world's electricity comes from wind, solar and other renewable sources (https:// www.un.org/science/causes and effects of climate change).
- The manufacturing industry is one of the major contributors to greenhouse gas emissions worldwide. Economic progress in the last six decades along with a rapid expansion of the global population has been achieved at a colossal environmental cost. While global GDP per capita has nearly tripled since 1960, CO_2 emissions have quadrupled during the same period (unctad.org). The world's top three emitters in 2021 are:
  1) China- 30.9%
  2) United States-13.5%. In 2018, the U.S. generated 291.4 million tons of trash - 12% of the waste generated across the globe for a region housing only 4% of the world's population. (Jane Courtnell, August 30, 2022).
  3) India- 7.3%

The above three account for about 50% of global CO_2 emissions.(Statista, Energy & Environment/emissions/2021)

China wanted to:

- achieve development at a fast pace
- eradicate poverty
- enhance integration in the global value chain

This added to an enormous expansion of the country's carbon emissions. The basic issue that the world is facing is that the emerging market economies, in trying to achieve their major economic goals of reduction in unemployment and poverty, have to utilise a large amount of fossil fuel. Alternative sources of energy are extremely expensive for developing economies. The problem that arises is that given the adverse impact of climate change on the world there seems to be no other alternative but to opt for the expensive alternative. The only hope is that with the mass production across all aspects of the economy, it is likely that production costs will come down due to the adoption of economies of scale.

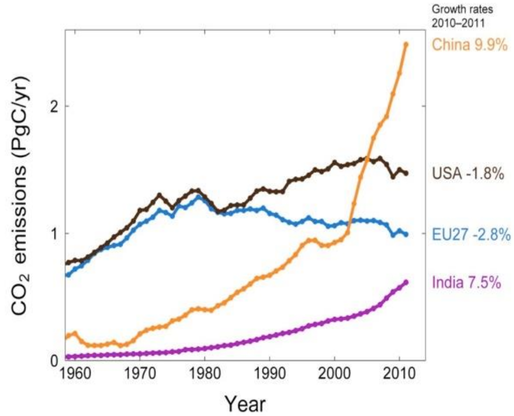


Figure 2: Image of CO_2 Emissions

Source: Max Planck Institute for Biogeochemistry, Jena

The figure above indicates the extent of carbon emissions by the two most populous economies of the world, namely India and China. To achieve lower levels of carbon emissions it is necessary to adopt carbon replacing technology in all sectors; agriculture, manufacturing and the services sector, and within them at each stage of the production process.

2. IMPACT OF ACCUMULATION OF WASTE

Packaging waste is that part of the waste that consists of packaging as well as packaging material. This forms a major part of the total global waste as it consists of single use plastic food packaging, which is part of the throwaway culture that the world has adopted. Packaging comes in all shapes and forms and is used to store, transport, contain, and protect goods all catering to customer satisfaction. Packaging material includes glass, aluminum, steel, paper, cardboard, plastic, wood and other miscellaneous packaging. Packaging waste is a dominant contributor in today's world and is responsible for half of the waste that is generated in the world. Packaging waste pollutes the earth. This negatively impacts marine and land living animals, by suffocating them. There has been a serious endeavor to educate the citizens on the separation of garbage as well as attempts to recycle the waste such that the impact on the environment is minimal.

Source: www.researchgate

Figure 3: Plastic waste generated in 2015

Source: Dreamstime

Figure 4: Description of waste material littering beaches

The figures above clearly indicate the type and extent of pollutants that have been generated in the world, resulting in the degradation of the environment. It is extremely essential to find alternative materials to replace the non-biodegradable materials that are presently being utilized. This has to be an endeavor at all levels. It is with respect to this, that various plants and plant-based materials are now being considered as alternatives to packaging materials. The main feature being that they are biodegradable, as they are natural-based products.

3. PLANT- BASED PACKAGING MATERIAL

"Plant-based" refers to materials and products that are partially or wholly derived from plants or other renewable agricultural, aquatic or forestry inputs. Plant-based raw materials come from trees or plants, including fruits, nuts, flowers, fungus, vegetables, resins, wood, and cotton. Some of the sustainable packaging strategies are:

- Share disposal and recycling best practices
- Recycled packaging materials
- Plant based packaging
- Edible packaging
- Plantable packaging
- Compostable and biodegradable plastic alternative.

Packaging is one of the foremost areas that can and should be addressed if sustainable practices are to be followed; controlling it would diminish the detrimental ecological footprint in all products' life-cycle steps.

Sustainable packaging minimizes the use of nonrenewable resources and lowers waste output through the use of eco-friendly materials and design techniques. It encourages recycling, composting, and repurposing, as well as preventing waste from going to landfills and being burnt, creating excessive amount of greenhouse gasses. Besides the above, it also strikes a balance between the demands of environment, consumer convenience and product protection, eventually lowering the environmental impact of packaging.

While choosing sustainable products for packaging it is essential to:

- Thoroughly assess the environmental footprints associated with different packaging materials.
- Evaluate factors such as carbon emissions, resource depletion and pollution potential.

It might seem impossible to imagine, but it is a fact that there are some incredible plastics that have been made entirely or partially from plant based materials. These are plastics that are derived from plant material like corn, starch, seaweed, sugarcane, tree pulp, and fungus and bamboo fiber.

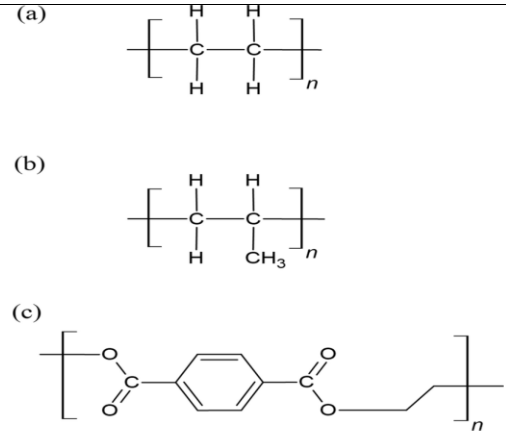
The packaging material that is made is environmental friendly as it requires less carbon to produce, reduces the amount of waste sent to landfill and produces no toxins as it breaks down. These plant-based plastics reduce the demand for fossil fuels that are used in the making of conventional plastic. The most common Bio-plastics are those derived from corn starch. These are often mixed with biodegradable polyesters. Polylactic acid is the most widely used plant-based plastic found in medical, agriculture and packaging applications.

Some of the packaging solutions are:

- Biodegradable packaging peanuts
- Corrugated bubble wrap
- Air pillows made from recycled content
- Cornstarch packaging
- Mushroom packaging
- Seaweed packaging
- Biodegradable plastics and recycled plastics
- Organic ecological textiles
- Edible films

4. IMPORTANCE OF BIODEGRADABLE PLANT BASED PACKAGING MATERIAL

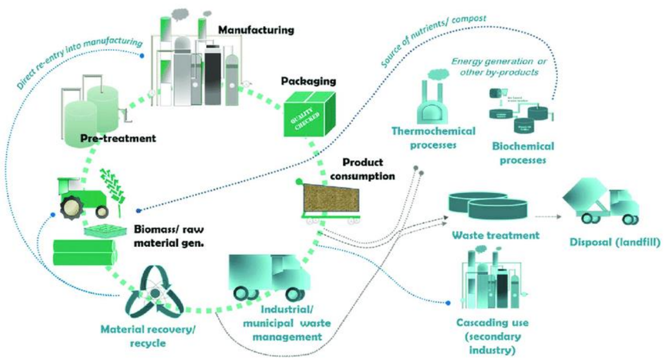
Most of the materials used in the packaging industries are derived from fossil fuels, and when they are used for storage packaging, they represent a serious environmental concern. Plastic production increased from 2.3 million tons in 1950 to about 450 million tons by 2015 and is expected to double by 2050 (European Bio plastics 2020 Market Development Update 2020). Discarded plastics enter the environment such as soil or ocean and are even found on the human body in the form of micro plastics. The above such alarming statistics have hastened the process of discovering newer forms of degradable packaging material, by using biodegradable polymers.



Source: www.researchgate

Figure 5: Chemical composition of (a) PE –polyethylene(b) PP-polypropylene (C) PET-polyethyleneterephthalate

But care should be advocated while using such material, as not all so called biodegradable plastic are bio-based; for example, Bio PET, the polyethylene terephthalate (PET) is produced from biomass which is not biodegradable, while those made from polycaprolactone are biodegradable.



Source: www.researchgate

Figure 5: Bio based value chain

It is well known that the amount of plastic material that is used specifically for food packaging is extremely high. The reason being that synthetic material prevents the transfer of water, gas, and flavorings between the wrapped or coated food and the surrounding medium. Food is increasingly being sold in grocery stores in plastic containers, often separated by multiple layers of plastic, then placed in plastic bags, especially for takeaway food, that might also contain plastic cutlery. The food sector is one of the biggest contributors to plastic pollution. Radical changes and innovations in the production system are needed to reverse this polluting process.

4. EVALUATION & COMPARISON OF DIFFERENT KINDS OF PLANT BASED MATERIAL

One of the most economical and accessible materials are plant based food waste and by-products (PWBs). More than 50% of fresh fruits and vegetables are wasted or lost from post harvesting to processing, storage and the consumer-end (2023, Food Packaging and Shelf Life). Typical examples of PWB materials are fruit pomace, husks, seeds, vegetable peels, crop biomass, or low quality whole fruits or vegetables.

Converting PWBs into packaging materials has a double benefit. Plenty of underutilized components exist in such food waste and by-products, namely plant-based poly saccharides, proteins, essential oils, organic acids or lipids (e.g. wax). These components can be used as major biomaterials or as minor additives which results in improved performance or different functionalities in packaging. Research has indicated that plant byproducts possess strong structural and functional characteristics that can enhance the biopolymer packaging with improved barrier and mechanical properties. The polyphenols that are present in the by-products such as peel, skin, roots, and seed significantly inhibited the lipid oxidation and microbial growth in the packed foods. The anthocyanin extracted from the skin, pomace, and bran incorporated films showed colour change due to pH variation(Permal, Leong, Chang, Seale, Hamid(2020)) These properties have the ability and the potential to develop intelligent and active packaging systems which can extend and monitor the shelf life of packed foods.

Biopolymers are naturally occurring macromolecules produced by plants, animals or microorganisms. Natural biopolymers include polysaccharides such as alginate, carrageenan, cellulose, chitin and chitosan, curdlan, gellan, pectin, pullulan, starch and xanthan and proteins such as collagen, gelatin, zein, soy, proteins and whey proteins (Priyadarshi et al, 2022) , which allow packaging materials to be sustainable and compostable. Biodegradable polymers are materials that can be degraded naturally by the action of microorganisms producing eco-friendly and useful materials such as CO_2 and CH_4. This is the reason for the growth of biopolymers in the interest of the environment. The main advantages are biocompatibility and biodegradability. The degradation process is as follows:

- Biodegradable: Degradation happens due to the presence of microorganisms
- Hydro-biodegradable: Degradation occurs in the presence of microorganisms and water
- Photo-degradable: Delinking between molecules in the presence of light
- Bio erodible: Degradation due to natural abrasion
- Compostable: Degradation occurs due to bacterial action that improves soil condition.

Some of the plant based products that are used as alternatives to plastic are:

- Fungal Mycelium
- Hemp hurd
- Cloth
- Paper Wool
- Algae

Amongst the plant based products mentioned above 'Fungal mycelium', seems to be the preferred alternative to plastic, as it exhibits a number of conducive properties like; limited use of water, light and space. It is home compostable which is desirable for single use applications such as packaging.

4.1 Definition of Fungi

Fungi are a group of multicellular eukaryotic, heterotrophs (cannot make their own food) non-phototrophic organisms with rigid cell walls, which includes mushrooms, molds and yeasts. They belong to a kingdom of organisms (Fungi) that lack chlorophyll, leaves, true stems and roots. They reproduce by spores and live as saprotrophs or parasites. They produce both sexually and asexually and have symbiotic associations with plants and bacteria.

Source: Pixel.com

Figure 6: Image of Fungi

4.2 Mycelium

Mycelium is a root like structure of a fungus consisting of a mass of branching, thread like hyphae. Fungal colonies composed of mycelium are found in and on soil and many other substrates. They often grow underground but can also thrive in other places such as rotting tree trunks. A single spore can develop into a mycelium. The fruiting bodies of fungi, such as mushrooms can sprout from a mycelium.

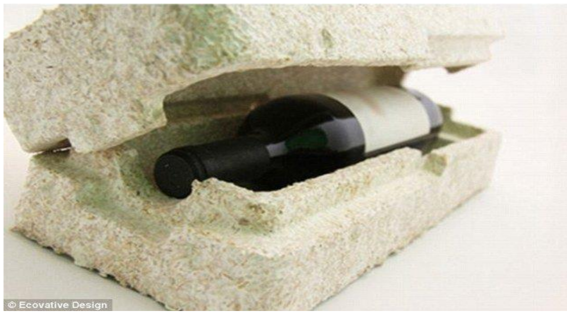
Source: naturamushroom.com

Figure 7: Image of Mycelium mushroom

It takes in small molecules of food- typically sugar, often from sources such as wood or plant waste- by excreting enzymes that break these materials down into digestible morsels. As the mycelium grows it resembles a dense 'Mycelium', which is partly like yeast, but unlike yeast cells which grow as a single cell, it is multicellular and can grow into macro size structures. Not only does mycelium produce small molecules, but assembles them into complex structures so small that they are invisible to the network of long, microscopic fibers that grow through the substrate like a superhighway system.

Research has indicated that the morphology and the mechanical characteristics of fungal mycelium can be manipulated to the desired structure by changing and optimizing their feed substrates, as their growth response has been shown to vary and depend largely on the medium of cultivation.

To use this product as a packaging alternative for sustainability purposes, it is essential to coax the mycelium to build predictable structures by controlling temperature, CO_2, humidity and airflow to influence the growth of tissue. Mycelium's fast growing fibres produce material for packaging, clothing, food and construction. It can be harnessed with the help of technology, in replacing plastics that are rapidly accumulating in the environment. Mycelium based foam and sandwich composites have been actively developed for construction structures. When clean, organic waste is brought in contact with mycelium, the fungus grows around the waste by growing roots and fibres that digest all of the waste. Finally, a solid block of mycelium is formed. This is later broken up and put into moulds that can be used to produce furniture, insulating panels, and bricks with increased thermal and acoustic properties.



Source: waterrush.info

Figure 8: Image of Mycelium Packaging

Source: biofab bio

Figure 9: Mycelium Packaging

5 ADVANTAGES OF USING MYCELIUM AS AN ALTERNATIVE PACKAGING AND CONSTRUCTION MATERIAL

Mycelium bio composite materials are capable of creating an impact in the area of sustainable packaging, and will make oil based plastic eventually obsolete, thus changing the way plastic impacts the environment.

The mycelium bio composite materials require minimum energy for their production, making it an extremely strong contender to expanded polystyrene in various packaging applications. As this material will quickly biodegrade in outdoor environment conditions, instances involving their burning in a landfill site will be rare.

The open cell structure of the mycelium composite material is the cushioning effect of the foam material which enables it as a suitable alternative for other toxic packaging material. The mycelium composite that was used was able to retain its dimensions without any deformation, decomposition or warping even after absorbing water, making it a viable substitute for plastic. As these composites have superior sound absorbing properties, they also have a greater potential in the field of sound insulation of walls, doors, and ceilings of concert halls. They are also capable of taking higher compressive loads, helping to reduce the thickness of material to be used for packaging, thus reducing cost.

The main positives in using mycelium derived materials are:

- Low cost material
- Low cost energy production
- Low density materials
- Low environmental impact and carbon footprint
- Biodegradable
- Good fire, thermal and acoustic insulation

6 DISADVANTAGES OF USING MYCELIUM AS AN ALTERNATIVE TO ENVIRONMENT HARMING MATERIALS

Mycelium has low structural strength and dries off when exposed to the environment, thus becoming inactive. Energy is required to sterilize the raw material before it can be used for cultivation. During this process of respiration, there is emission of CO_2, and in this way fungi are similar to animals rather than plants. They also have low tensile strength, poor handling properties, and lack of uniformity in thickness. Mushrooms typically require a dark space to grow. Unfortunately the smell becomes fairly intense as the mushrooms grow and it worsens over time. Fungi also constitute the largest number of plant pathogens which are responsible for serious plant diseases.

Fungal pathogens are extremely dangerous, and may cause the loss of crop harvests or, in the most serious cases, the death of plants. They can also negatively affect the quality of crops, causing an accumulation of toxins within the plants. These toxins could be dangerous for both humans and animals.

7. CONCLUSION AND THE WAY AHEAD

Given the seriousness of the deterioration of the environment in recent years, it has become extremely imperative to find an alternative to various materials that are harming the environment. One of the products that can be a strong contender to plastic, as well as an important part of the construction industry is Mycelium. Research has indicated that this product has far greater advantages rather than disadvantages, and would be a great asset in saving the environment for future generations. Universal use of this item as a sustainable alternative would make it accessible to all and would eventually cost the same as plastic. Concerted research and development is required by the government as well as private entrepreneurs to save the environment to make this a viable alternative.

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