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Review Article

PLASTICS AND MICROPLASTICS IN MODERN SOCIETY: BENEFITS, EMERGING APPLICATIONS, ENVIRONMENTAL CONCERNS, AND RECYCLING APPROACHES

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ABSTRACT:

Plastics are synthetic polymers derived primarily from petrochemicals, known for their versatility, durability, and low cost. They are widely used across industries, including packaging, construction, automotive, and healthcare. However, their resistance to degradation has led to significant environmental concerns, particularly regarding pollution and waste management. Efforts are underway to develop biodegradable alternatives and improve recycling technologies. Addressing the challenges posed by plastics requires a combination of innovation, policy, and public awareness. The widespread use of plastics and their persistent nature have led to the global proliferation of microplastics—tiny plastic particles less than 5 mm in size—that pose severe threats to ecosystems and human health. Microplastics result from the breakdown of larger plastic debris and are resistant to natural degradation processes, enabling them to accumulate in soil, freshwater, marine environments, and even the food chain. This paper explores emerging strategies for microplastic degradation, including advanced chemical, biological, and photocatalytic methods that aim to accelerate breakdown into harmless byproducts. Simultaneously, plastic reuse has emerged as a vital component of sustainable waste management, aiming to reduce plastic pollution at the source. Techniques such as mechanical recycling, chemical upcycling, and innovative reuse in construction and packaging industries offer promising solutions. Integrating degradation technologies with circular economy practices enhances the potential to mitigate environmental pollution, conserve resources, and promote a more sustainable relationship with plastic materials.

KEY WORDS: Plastics, Microplastics, Applications of plastics, Environmental impact, Plastic recycling, Plastic reuse, Sustainable materials, Waste management.

INTRODUCTION

Plastic is defined as a material that contains an essential ingredient an organic substance of large molecular weight. It is also defined as polymers of long carbon chains. The word plastic was derived from the word plastikos meaning to mould in Greek.[1] It is very difficult to realise how important plastics have become to our everyday lives. we always seem to have known these materials and we tend to take it for granted that they occur every day and all around us for example in our clothing, the pen that we write with the chair that we sit on or the wrapping of the food that we eat. look around you; how much plastic do you see? So it is sometimes hard to believe that plastics have only been commonly available for about the last one hundred years. Yet in this time the impact that they have made upon the quality of our lives and on the products that we have access to has been enormous. Plastics give us the possibility of manufacturing well-designed, beautiful products from the very many different types of plastics materials that are commonly available today. Within manufacturing technology there is a very high degree of technological understanding of plastics and a range of sophisticated technological processes that enable us to make them and shape them in numerous ways[2].

History of plastic: The development of plastics began with Alexander Parkes, who introduced parkesine (a cellulose-based material) in 1862. Later, John Wesley Hyatt invented celluloid in 1868 as a substitute for ivory

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in billiard balls by combining cellulose with camphor. Celluloid became the first flexible photographic film, playing a crucial role in early photography and cinema. By the early 1900s, formaldehyde-based plastics emerged. Casein plastics (milk protein and formaldehyde) were used for chalkboards, and Arthur Smith patented phenol-formaldehyde resins in 1899. However, in 1907, Leo Baekeland developed Bakelite, the first fully synthetic plastic, revolutionizing materials science by freeing humans from reliance on scarce natural resources. Plastics not only helped conserve materials like ivory and tortoiseshell but also democratized material wealth, making goods more affordable. The plastics industry boomed during World War II, providing synthetic alternatives (e.g., nylon, Plexiglas) essential for the war effort. U.S. plastic production increased by 300% during the war. Post-war, plastics rapidly replaced traditional materials like steel, glass, paper, and wood in everyday products. They symbolized modernity, abundance, and innovation, shaping a future fueled by inexpensive, versatile materials.[3,4]

Table: 1.1 composition of plastic[5]

Plastic composition	percentage
Low density poly ethylene	24%
high density poly ethylene	13%
polyprolene	19%
Pvc	19%
polystyrene	6%
pet	6%
others	10%

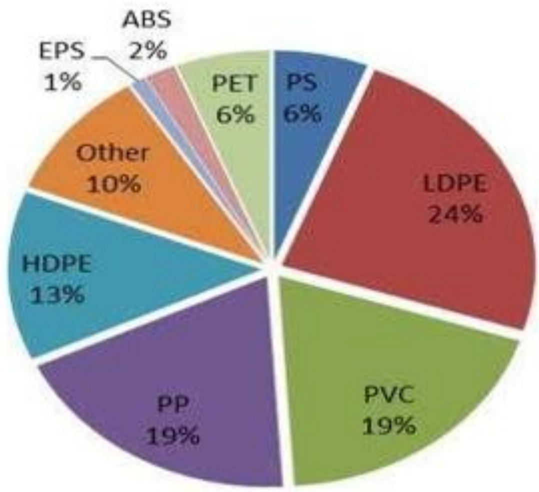

Fig: 1 Composition of Plastic

2. Types of plastic: Thermoplastic: Plastics that can be deformed easily upon heating and can be bent easily linear polymers and a combination of cross linked polymers comes under thermoplastics. Example: Pvc, nylon, polythene. Thermosetting; Plastic that cannot be softend again by heating once they are moulded. heavily cross -linked polymers comes under the category of thermosetting plastics. Example: Bakelite, melamine6. Polyethylene Terephthalate: sometimes absorbs odours and flavours from foods and drinks that are stored in them. Items made from this plastic are commonly recycled. PET(E) plastic is used to make many common household items like beverage bottles, medicine jars, rope, clothing and carpet fibre High-Density Polyethylene: products are very safe and are not known to transmit any chemicals into foods or drinks. HDPE products are commonly recycled. Items made from this plastic include containers for milk, motor oil, shampoos and conditioners, soap bottles, detergents, and bleaches. Polyvinyl Chloride: is sometimes recycled. PVC is used for all kinds of pipes and tiles, but is most commonly found in plumbing pipes. Low-Density Polyethylene: is sometimes recycled. It is a very healthy plastic that tends to be both durable and flexible. Items such as cling-film, sandwich bags, squeezable bottles, and plastic grocery bags are made from LDPE. Polypropylene: -is occasionally recycled. PP is strong and can usually withstand higher temperatures. It is used to make lunch boxes, margarine containers, yogurt pots, syrup bottles, prescription bottles. Plastic bottle caps are often made from PP. Polystyrene: is commonly recycled, but is difficult to do. Items such as disposable coffee cups, plastic food boxes, plastic cutlery and packing foam are made from PS. Miscellaneous: types of plastic not defined by

the other six codes. Polycarbonate and Polylactide are included in this category. These types of plastics are difficult to recycle. Polycarbonate (PC) is used in baby bottles, compact discs, and medical storage containers[7].
3. Importance to recycle plastic. Re-using and recycling items as many times as possible can reduce our need to create new plastic. This means we can:-conserve non-renewable fossil fuels ,reduce the consumption of energy used in the production of new plastic,reduce the amount of solid waste going to landfill reduce emission of gases like carbon dioxide into the atmosphere[8].

PLASTIC RECYCLING: It includes following steps: Collection and Distribution: In this step, collectors from the government or private companies gather all post-consumer materials from establishments like homes, schools, and other institutions. Sorting and Categorizing: Sorting entails grouping plastics into their respective types. Beyond chemical composition, sorting is also done by color, thickness, and usage. This step can be done manually or by machines at recycling plants. Washing: Washing is the process of removing all the impurities that may impede the following processes. Here, product labels, adhesives, and food residue are removed. Shredding:-After washing comes shredding, which is basically breaking down the sorted and washed plastics into smaller-sized pieces. In this state, they might be used as additives within asphalt or sold as a raw material. Shredding also allows the removal of more impurities like metals. Identification and Separation: Here, plastics are tested for their class and quality. So, they are first segregated based on density, where testing is done by floatation on water. The next process is called air classification, where plastics are categorized based on thickness. Air classification occurs in a wind tunnel—thinner pieces float while thicker ones stay at the bottom. Extruding and Compounding: The final stage of plastic recycling is when the plastics are crushed and melted to form pallets called nurdles. After they become nurdles, they are transformed to take a new shape to make a new product. Please note that different classes of plastics might need specific plants to finalize this step.[9,10]

Fig:-1.2 Seven types of plastics

1.Methods of plastic recycling: Mechanical recycling: offers significant advantages in terms of a circular economy for post-consumer plastic waste, leading to the conservation of finite resources and a reduction in GHG emissions Various types of plastic waste originate from municipal, agro-based, livestock, industrial areas, and commercial workshops. Before engaging in the mechanical recycling of post-consumer plastic waste, the collected plastic materials are combined with other substances such as cans, glass, additional polymers, and chemical additives. These materials undergo several pretreatment steps, including separation, washing, cutting, grinding, and pelletization Extrusion technologies are commonly used for mechanical recycling. These systems comprise a feed section, where plastic waste is introduced, a barrel containing a compression section, and one or two screws for melting the flaked plastic waste. Extrusion can lead to the decomposition of the melt polymers, producing monomers or oligomers. This decomposition can be controlled to a certain extent by adjusting parameters such as the heating temperature and screw speed. During extrusion, various types of bond cleavage and formation among polymers can occur, affecting polymer properties. Undesirable outcomes such as crosslinking and branch formation can lead to deteriorated physical and chemical properties, resulting in low-quality products. Polymer modifications, including crosslinking and isomerization due to branch group formation can degrade their physical and chemical properties An extrusion system with space to reserve the polymer in the molten state before double screws was drafted to improve the quality of recycled polymer products. Generally, extruders can operate with a single-screw or a double-screw system and their choice depends on the specific requirements of the application. Additionally, different types of extrusion processes can be utilized based on the desired product shape, including continuous production using compressed air to expand plastic tubes, injection molding for items such as kitchenware, and blow molding for containers and vessels with lid-film blowing techniques to produce thin-film tubes for items such as bags or sacks. Extruder design significantly influences the quality of recycled products. Polymers produced using an extruder equipped with a molten resin reservoir (MSR) exhibit a laminar structure aligned with the flow direction. In contrast, the polymers produced from double-screw extruders without an MSR exhibit irregularly dispersed structures. Recycled polymers produced via extrusion processes equipped with an MSR can maintain a structure similar to that of virgin polymers.[11]

2. Chemical recycling: Chemical recycling is the process of converting polymeric waste by changing its chemical structure and turning it back into substances that can be used as raw materials for the manufacturing of plastics or other products. There are different chemical recycling technologies, e.g. pyrolysis, gasification, hydro-cracking and depolymerisation.[12]

MICROPLASTIC

Microplastics are fragments of any type of plastic less than 5mm (0.20 in) in length. They enter natural ecosystems from a variety of sources, including cosmetics, clothing, and industrial processes. Microplastics may be primary microplastics that include any plastic fragments or particles that are already 5.0 mm in size or less before entering the environment. These include microfibers from clothing, microbeads, and plastic pellets (also known as nurdles). Or secondary microplastics arise from the degradation (breakdown) of larger plastic products through natural weathering processes after entering the environment. Such sources of secondary microplastics include water and soda bottles, fishing nets, plastic bags, microwave containers, and tea bags. Both types are recognized to persist in the environment at high levels, particularly in aquatic and marine ecosystems. However, microplastics also accumulate in the air and terrestrial ecosystems. Because plastics degrade slowly (often over hundreds to thousands of years), microplastics have a high probability of ingestion, incorporation into, and accumulation in the bodies and tissues of many organisms. The toxic chemicals that come from both the ocean and runoff can also bio magnify up the food chain . Microplastic pollutants is currently an important topic in both industry and academia, as well as among legislative bodies, and research in this area is gaining considerable attention from both the worldwide media and scientific community on a rapidly increasing scale.13

1. Separation of microplastic from water :- Taking advantage of solid MPs/NPs' small particle size, unable hydrophobicity, and rich functional groups, diverse efficient techniques have been employed for MP/NP separation from aqueous matrices. Specifically, in wastewater treatment plants (WWTPs), it is proved that preliminary and primary treatments and secondary treatments remove over 80% of MPs, where the preliminary and primary treatments are the most effective. This separation efficiency can further increase to ∼98% by the application.

To date, diverse methods have been employed to separate and degrade MPs/NPs in urban waters. The separation process mainly focuses on taking tiny MPs/NPs particles out of the solution, and the properties (e.g., size, chemical composition) of MPs/NPs generally remain unchanged during the separation procedure. Many sophisticated solid-liquid separation techniques have been implemented in separating MPs/NPs from waters, such as adsorption, coagulation/flocculation, flotation, filtration, and magnetic separation . The selection of separation methods relies on MPs/NPs' physicochemical characteristics (e.g., hydrophilicity, size, shape, magnetic properties), and the separation performance highly relies on technical parameters and the involved functional materials (e.g., adsorbents). For example, plastics magnetized by nano-Fe3O4 can be easily removed from waters via the magnetic separation process. Beyond the application of a single process, integrated methods which combine the features of individual techniques are widely used to enhance separation efficiency In this review, we aim to comprehensively review recent advances in the separation and degradation of MPs/NPs in urban waters. First, efficient strategies for the separation of MPs/NPs from urban waters are summarized, including adsorption, coagulation/flocculation, flotation, filtration, and magnetic separation. Then, recent advances in the degradation of MPs/NPs in urban waters are analyzed, and methods like electrochemical degradation, AOPs, photodegradation, photocatalytic degradation, and biological degradation are detailed. Importantly, critical functional materials and operational parameters within the separation and degradation of MPs/NPs are discussed.[14]

2.Separation of microplastics from air:- Afterward, the current challenges and prospects (e.g., reutilization of MPs/NPs from urban waters) are proposed.[13] polypropylene microplastics are removed from the air by using air dielectric barrier discharge[15, 16]

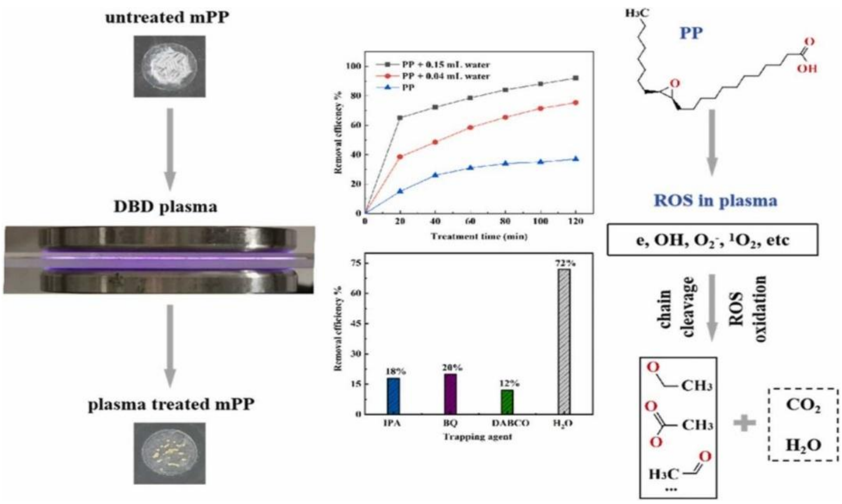

Fig: 1.3 separation of microplastic from air by air dielectric barrier discharge method

At present, there are several different methods for the degradation of microplastics: biodegradation [17] photodegradation [17], [18], chemical degradation [19], thermal degradation [20], [21], membrane filtration [22], [23], hydrothermal carbonization [24], etc., but generally long degradation time and low efficiency. Plasma technology is a kind of advanced oxidation technology, because of its fast and efficient equipment, simple and easy operation, green and environmental protection advantages. Dielectric barrier discharge (DBD) belongs to the category of low-temperature plasma, it is widely used in the fields of environment[25] In the process, strongly oxidized substances (•OH, •O, O3, H2O2, etc.), as well as electromagnetic radiation (visible light, photons) and ultraviolet light cooperate, making organic macromolecules undergo ring opening and bond break reactions, and finally degrade into carbon dioxide, water and inorganic ions to achieve the complete mineralization of organic pollutants and macromolecules [26], [27] Compared with traditional processes such as Fenton [19] O3 / H2O2, UV / O3 and UV / H2O2, the plasma can achieve strong oxidation without the addition of any chemical material modification [28].

3.Separation of microplastic from soil:- The large amounts of microplastics in farmlands have prompted research ranging from environmental and health impacts to effects on soil physical and hydraulic properties. A growing number of studies have shown that microplastics have a significant effect on soil physical properties and water movement. Among them, most studies have shown that microplastics can alter soil structure by clogging soil pores, leading to increased soil bulk density and decreased saturated hydraulic conductivity.[29]Soil field capacity, plant-available water content, and the wilting point also decrease.[29] These effects are modulated by the type, size, and concentration of microplastics. For example, polyester fibers reduce the volume of pores smaller than 30 μm while increasing the volume of pores larger than 30 μm in clay soil.[30] Smaller microplastics (150 μm) have been found to increase the water retention capacity of a loam soil, whereas larger microplastics (950 μm) reduced the water retention capacity in a sandy soil [31] .Furthermore, microplastics had a greater negative impact on the saturated hydraulic conductivity (Ks) of sand soil compared to loam and clay soils.[30] However, the effects of microplastics on soil physical and hydraulic properties might have been exaggerated and misinterpreted in many of the above cases due to the different soil sample preparation methods. For instance, found that when soil samples are amended with microplastics and compressed with a constant stress, microplastics had only minimal impacts on soil physical properties. Contrary to most of the previous results .[29]which compressed soil samples with a constant bulk density, volume or void ratio as the control ,found that Ks increased in microplastic-amended samples under constant stress soil preparation.[[29,30,31,][32] [33,34,35,36,37]

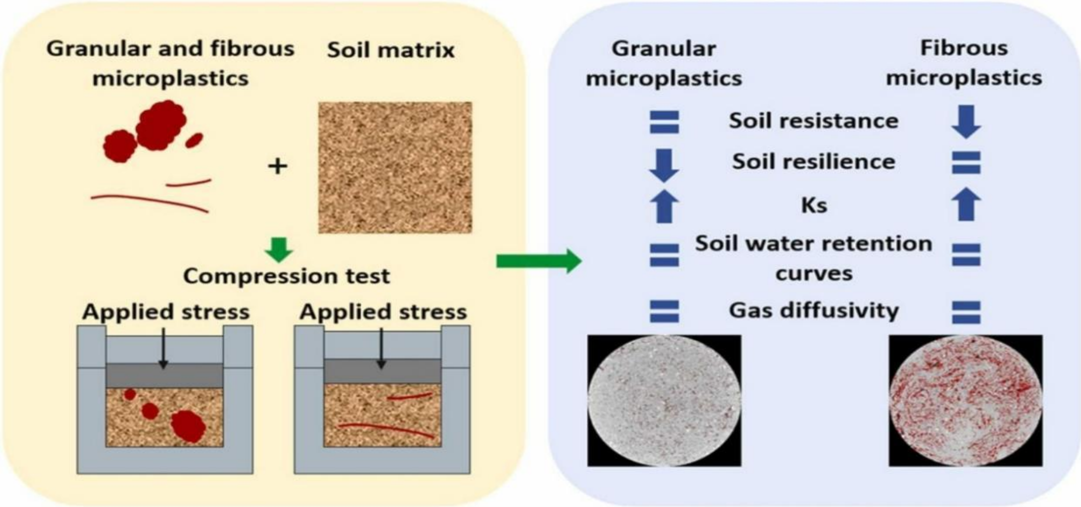

Fig:-1.4 seperation of microplastics from the soil

Table: 1.2 Different types of bio-degradable and non-bio-degradable microplastic

Bio degradable and non bio degradable	Types of microplastics	Appplications
Biodegrable microplastics	Polylactic acid [PLA] Poly capro lactole[PLC]	Use in Bottles,plastic film Used in medical devices
non bio degrable microplastic	Polyethyelene Terepthalate[PET] Polyethylene [PE] Polystyrene [PS]	Used in water bottles Used in plastic bottles and cans Used in food cans

Enzymatic degradation: Generally, the mechanisms of degradation of MPs depend upon the different factors such as the chemical structure of plastic polymer, molecular weight of chemical compounds, plasticizer and additives used for making plastics. [38] Various biochemical reactions are involved in the degradation of microplastic by microorganisms. Microorganisms (Bacillus sp., Ideonella sakaiensis, Rhodococcus sp. And Paenibacillus sp. etc.) secretes different varieties of enzymes (esterase, urease, lipase, protease, glycoside hydrolases and laccase), these enzymes get attached on the backbone of long chain plastic polymers and cleave long chain of polymer into monomers units. The first and most important step of degradation is the hydrolysis of microplastic to improve the hydrophobicity by the enzymes by offering the functional group of the microplastic polymers [38,39]

Enzymatic degradation of MPs is divided in two different groups; hydrolysable (PET) and non-hydrolysable (PE, PS and PP). Enzymes reported for degradation of PET includes cutinase, PETase and MHETase. Cutinase enzyme secreted by Fusarium solani degrades the PET through breakdown of both the aliphatic and aromatic ester bonds of polyester.[40] Cutinase enzyme performs biodegradation at optimum pH range and temperature at 50–55 °C. PETase enzyme secreted by microorganism (Ideonella siakensis) breaks the aromatic ester bond of polyester and performs degradation at pH value 7 to 9 [40,41] MHETase cause nucleophillic attack on the carbon atom of polyester. It requires optimum pH of 6.5–9 and a temperature 45 °C [41] PE degradation is completed by two intracellular enzymes, such as polyethylene glycol(PEG) dehydrogenase and alkane hydrolase. PEG dehydrogenase cleaves the PEG and produces glyoxylic acid while alkane hydrolases cleaves polyethylene microplastic at optimum temperature of 45 °C and pH 4.5[42] Similarly for PS degradation, different enzymes are capable to form single ring aromatic compounds and hydrolyze the C\\C bond. Bacillus subtilis, Sphingomomonas paucimobilis, Alcanivorax borkumensis secretes Cytochrome P450CPX152A1, CytochromeP450CPX152B1, Cytochrome CPX153s, respectively to catalyze oxidation of styrene and hydroxylation of ethyl benzene. These enzymes play an important role in the conversion of alkane to alcohol [43]. Hydrolytic enzyme (esterase) has been reported for degradation of PS, this enzyme breakdown the polymer into smaller fragments at an optimum temperature of 45°C at pH 9[44]

Oxidation mechanism: In this process, degradation of organic pollutants is based on the formation of reactive oxygen species[45] These reactive oxygen species directly activate the degradation process by breaking the long polymer chain and completing the degradation cycle by forming useful products [46]

a. Photocatalytic degradation: Photo catalytic degradation is a green technique to decompose organic pollutants by employing free solar energy. This process is based on the decomposition of semiconductor components of organic pollutant. In this process decomposition starts when the photon energy of semiconductor components is too much higher than the gap energy of semiconductor substance The valence band electrons easily transfer to the conduction band and cause a positive hole in the valence band of semiconductor substance resulting in the partition of electron holes[45]

b. Photochemical degradation:- is another method for decomposing organic pollutants. Ultra violet (UV) light plays an important role in photochemical degradation[47] Organic pollutants decomposed through long-time exposure to UV light results in the formation of oxygen free radicals and cross-linked the long chain of polymers[48]

c. Electro chemical degradation: This method is based on the anodic and cathodic surface degradation of pollutants. Anodic degradation causes direct oxidation by transferring the charge on the anode surface of pollutants and indirect oxidation by reactive oxygen species and H2O2. Cathodic degradation is completed by Electron Fenton technique and oxygen free radicals. It is generated by Fe+ and is responsible for degradation of MPs[45]

CONCLUSION:

Plastic and microplastic pollution has emerged as a critical environmental challenge due to their durability, resistance to degradation, and widespread use. Effective reuse and biodegradation strategies are essential to mitigate their impact on ecosystems and human health. Reuse of plastics through recycling, upcycling, and circular economy practices can significantly reduce the volume of waste entering natural environments. Meanwhile, advances in biodegradation using microbial, enzymatic, and chemical processes offer promising solutions for breaking down persistent plastic pollutants, including

However, these approaches face technical, economic, and social barriers that must be overcome through innovation, policy support, and public awareness. Ultimately, a combined approach involving reduction in plastic use, improved waste management, reuse, and sustainable biodegradation technologies is essential for creating a cleaner and more sustainable future.

FUTURE SCOPE:

14.Plastic To Paracetamol: Scientists Convert Waste Into Painkiller New research from the University of Edinburgh in the UK has achieved a significant breakthrough by using Escherichia coli bacteria to convert molecules from polyethylene terephthalate (PET) plastic into acetaminophen, commonly known as paracetamol. This offers a promising approach to addressing both plastic pollution and the reliance on fossil fuels in drug manufacturing. Acetaminophen is typically produced using fossil fuels. Replacing these ingredients with waste products like plastic could provide an innovative solution to two major environmental challenges. While scaling up the process and demonstrating its industrial and commercial viability will take time, this new technology holds considerable potential for sustainable drug production and waste management As per a news release by the University of Edinburgh, this process has several benefits, including: Quick Turnaround: Results can be obtained within 24 hours. Compact Setup: It can be performed in a small laboratory setting. Energy Efficiency: It operates at room temperature, eliminating the need for extreme heating or cooling. This work demonstrates that PET plastic isn't just waste or a material destined to become more plastic - it can be transformed by microorganisms into valuable new products, including those with potential for treating disease," says biotechnologist Stephen Wallace from the University of Edinburgh. Experts say this new approach demonstrates how traditional chemistry can work with engineering biology to create living microbial factories capable of producing sustainable chemicals while also reducing waste, greenhouse gas emissions and reliance on fossil fuels.

15. Built houses made up of plastic wastes:

The global multi-layered packaging (MLP) market is on a steady rise, expected to reach USD 211.64 Million by 2029, growing at a CAGR of 4.60% from 2022 to 2029. These multilayer structures, consisting of three or more layers of materials like polyolefins, PET, PVDC, PA, EVOH, aluminium, paper, and more, cater to the packaging needs of fast-moving consumer goods (FMCG) companies constituting around 25% of all plastic packaging produced globally. However, their convenience comes at a cost to the environment. Multilayer plastics (MLPs) are difficult to recycle due to their complex structure. Most urban local bodies must pay to send them to waste-to-energy or cement plants.Here, MLPs are often burned, disguised as “energy recovery”. About 2.6 million tons of MLPs are incinerated or landfilled every year.Challenges include classification, layer separation, and high processing costs. The EU is leading global regulatory efforts on plastic waste. Its laws require 65% of all packaging waste, including MLPs, to be recycled by 2025.The U.S. lacks a federal mandate, so states like California act independently.Canada and Japan enforce strict recycling targets for multilayered containers.Australia uses a voluntary scheme for 100% recyclable or compostable packaging. The Intergovernmental Negotiation Committee (INC4) is drafting a global plastics treaty.This treaty will cover the entire lifecycle of plastics, including MLPs. Global production of multilayer plastics could reach 6.5 million tons by 2027. New regulations aim to curb the environmental impact of these materials. Tackling MLPs is crucial for sustainable packaging and waste management.

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