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Review

Bioplastic classifications and innovations in antibacterial, antifungal, and antioxidant applications

Sariah Abang[a,*], Farrah Wong[b], Rosalam Sarbatly[c], Jamilah Sariau[c], Rubiyah Baini[a], Normah Awang Besar[d]

[a] *Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan 94300, Malaysia*
[b] *Electronic Engineering (Computer) Programme, Faculty of Engineering, Universiti Malaysia Sabah, Kota Kinabalu 88400, Malaysia*
[c] *Chemical Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Kota Kinabalu 88400, Malaysia*
[d] *Forest Plantation and Agroforestry Programme, Faculty of Tropical Forestry, Universiti Malaysia Sabah, Kota Kinabalu 88400, Malaysia*

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ABSTRACT

Conventional plastics exacerbate climate change by generating substantial amounts of greenhouse gases and solid wastes throughout their lifecycle. To address the environmental and economic challenges associated with petroleum-based plastics, bioplastics have emerged as a viable alternative. Bioplastics are a type of plastic that are either biobased, biodegradable, or both. Due to their biodegradability and renewability, bioplastics are established as earth-friendly materials that can replace nonrenewable plastics. However, early bioplastic development has been hindered by higher production costs and inferior mechanical and barrier properties compared to conventional plastics. Nevertheless, studies have shown that the addition of additives and fillers can enhance bioplastic properties. Recent advancements in bioplastics have incorporated special additives like antibacterial, antifungal, and antioxidant agents, offering added values and unique properties for specific applications in various sectors. For instance, integrating antibacterial additives into bioplastics enables the creation of active food packaging, extending the shelf-life of food by inhibiting spoilage-causing bacteria and microorganisms. Moreover, bioplastics with antioxidant additives can be applied in wound dressings, accelerating wound healing by preventing oxidative damage to cells and tissues. These innovative bioplastic developments offer promising opportunities for developing sustainable and practical solutions in various fields. Within this review are two main focuses: an outline of the bioplastic classifications to understand how they fit in as the coveted conventional plastics substitute and an overview of the recent bioplastic innovations in the antibacterial, antifungal, and antioxidant applications. We cover the use of different polymers and additives, presenting the findings and potential applications within the last decade. Although current research primarily focuses on food packaging and biomedicine, the exploration of bioplastics with specialized properties is still in its early stages, offering a wide range of undiscovered opportunities.

1. Introduction

Plastics play an integral role in almost all aspects of human life, particularly in packaging foods, beverages, and various other products. There is an extremely high demand for plastics in the market. In 2021, the packaging sector held the largest market share

* Corresponding author.
E-mail address: asariah@unimas.my (S. Abang).

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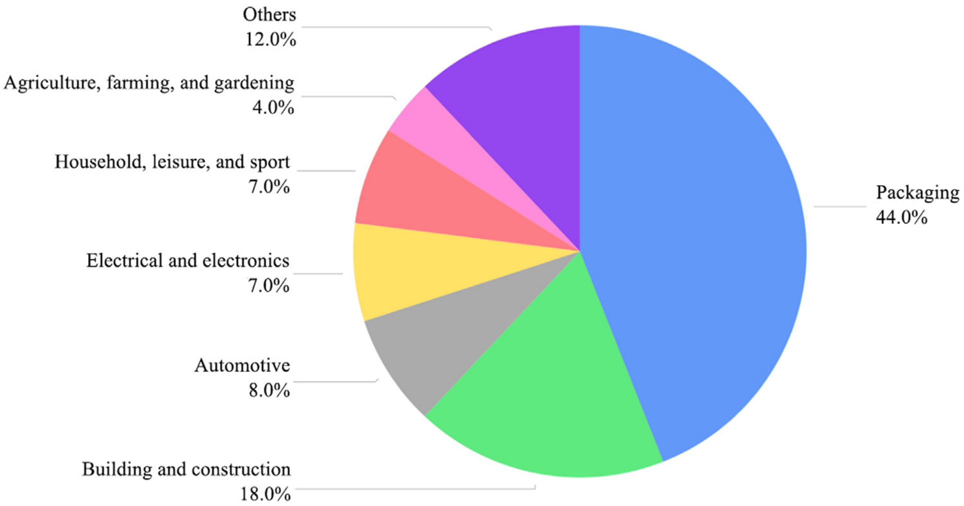

Fig. 1. Plastics use by market segment (2021) (adapted from Plastics Europe (2022)).

at 44%, followed by building and construction (18%), automotive (8%), electrical and electronics (7%), household, leisure and sports (7%), agriculture, farming and gardening (4%), and others (12%), as shown in Fig. 1. The global plastics production in 2021 stood at 390.7 million tons, a 4% increase from the previous year (Plastics Europe, 2022). Despite growing concerns raised by environmental activists regarding global pollution, the demand for plastics is projected to continue rising at a compound annual growth rate (CAGR) of 3.5% (Tiseo, 2021).

Plastic is a broad term that describes materials that can be formed and molded under heat and pressure. It is made from polymers, which are large molecules made up of smaller repeating units called monomers. The majority of plastics, such as polypropylene (PP), polyethylene (PE), poly(vinyl chloride) (PVC), polystyrene (PS), polyamide (PA), and poly(ethylene terephthalate) (PET), are currently derived from nonrenewable petroleum sources. These petroleum-based plastics possess good mechanical strengths, effective gas barriers, heat sealability, and are widely available at low costs, making them ideal for various product manufacturing (Naveena and Sharma, 2020). However, a significant drawback is that a significant portion of these synthetic plastics is not biodegradable, leading to environmental concerns due to the accumulation of solid wastes (Ibrahim et al., 2021). As a result, tremendous amounts of plastic waste are generated. In 2020, almost 86 million tons of plastic waste found its way into landfills, where it continues to accumulate and persist for a long time. The complete breakdown of plastics can take anywhere from 10–600 years (Mohanan et al., 2020), depending on the material and structure. This is further aggravated by plastic polymer deterioration which produces a high amount of microplastics that pollute the environment and pose significant threats to human health and nature. The health implications of microplastic deposits in our bodies have not been fully known since they were only discovered less than two decades ago. Furthermore, plastics may contain toxic components such as phthalates, poly-fluorinated chemicals, bisphenol A (BPA), brominated flame retardants, and antimony trioxide. These components have the potential to leach out and contaminate the groundwater or be absorbed by plants and marine organisms, thereby entering the food chain (Alabi et al., 2019).

The existing environmental challenges serve as motivation for researchers to contribute to plastic research, aiming to develop environmentally friendly and biodegradable materials like bioplastics. The term "bioplastic" is used to distinguish polymeric materials that are biobased, biodegradable, or both (European Bioplastics, 2022a). Bioplastics are characterized by their remarkable biodegradability, which contributes to reducing environmental hazards (Ibrahim et al., 2021). Biobased materials consist of substance originating from living matter or biomass and occur naturally or synthesized, or they may refer to materials produced by processes that use biomass (Curran, 2010). Conversely, biodegradability refers to the ability of microorganisms to decompose a material into smaller components like carbon dioxide, water, and biomass. In theory, all plastics are degradable, but most petroleum-based plastics degrade at an exceedingly slow pace and are therefore regarded as non(bio)degradable. Bioplastics are considered more sustainable than conventional plastics since they generate fewer greenhouse gases throughout their lifecycle (Coppola et al., 2021). The carbon dioxide released during production, usage, and recycling is offset by the carbon dioxide absorbed during the growth phase of the plants used to produce bioplastics, which significantly reduces the total carbon dioxide balance (Ibrahim et al., 2021). Fahim et al. (2019) found that as much as 800 million tons of greenhouse gas emissions can be reduced yearly by replacing all synthetic plastics with poly(lactic acid) (PLA), a bioplastic material, and recycling the plastics generated every year. Bioplastics made from biodegradable and biobased materials are regarded as the greenest alternative to petroleum-based plastics. Their biocompatibility and biodegradability make them particularly suitable for applications in packaging, biomedical, and other valuable industrial applications (Nanda et al., 2022). According to Di Bartolo et al. (2021), bioplastics currently have a market presence in various sectors, including packaging, biomedicine, carrier and compost bags, agriculture and horticulture, and automotive and electronic manufacturing. Despite currently representing less than one percent of the total global plastic production, bioplastics are projected to experience annual growth rates of over 200% by 2026 (European Bioplastics, 2021). As a promising alternative to conventional plastics, bioplastics have