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A Review Paper on Starting Materials, Processes and Characteristics of Bio-Based Foams

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Abstract*:* *Bio foam products have attracted considerable attention lately because there is a growing demand for green/sustainable products. To this end, various biobased foams have either been developed or are currently in development, e.g., bio-based polyurethanes (PUs), polylactic acid (PLA), starch, and polyhydroxyalkanotates (PHAs). Indeed, significant progress has been made; however, challenges still persist, for example, biobased foam products have poor processability, inferior compatibility, thermal and strength properties. In this review, we focus on five biofoam products namely bio-based PUs, PLA, starch, PHAs, and cellulose biofoam products, along with their properties and performance, as well as their manufacturing processes. Further efforts are still needed to unlock the full potential of these bio-based products and meet the goal of complementing and gradually replacing some of their fossil-based counterparts. Finally, the challenges, as well as arising opportunities of future research directions are discussed.*

Keywords: Bio foam, Bio-based polyurethanes Polylactic acid

I. INTRODUCTION

Traditional foam products are made of synthetic polymers, mostly polyolefins, that are derived from fossil fuels (Pilla, 2011). Polyolefins are commodity polymers with low costs that are highly adopted and thus suited for foam products (Okoroafor and Frisch, 1995). However, synthetic polymer-based foam products have significant environmental impacts, such as landfill issues and marine pollution. Besides, the micro- and nano-size plastics can form under specific marine conditions (Chubarenko et al., 2016). Regulatory authorities are taking progressive steps to pass laws and regulations to limit the manufacture, sale, use, and disposal of conventional plastic products to minimize their environmental impacts. The new regulations will further transform the market, and lead to active research and development activities for biobased foam products. In this review, we focus on the present status and future outlook of bio-based foam products. The first part covers conventional foam products, their manufacturing processes, and their properties. In the second part, different bio-based foam products that are of most practical interest are discussed, with a focus on their properties, pros, and cons. These include bio-based polyurethanes (PUs), starch, cellulose, polylactic acid, and polyhydroxyalkanotates (PHAs). Finally, we put forward a summary and future perspectives.

II. CONVENTIONAL PLASTIC FOAM PRODUCTS

2.1. General manufacturing process

There are various foaming methods that are commercially practiced, including extrusion, compression molding, injection molding, and solid-state molding. The foam products, containing two-phase systems with uniform dispersion in the gas phase, and a stable and high-viscosity melt phase, are commonly processed in a continuous liquid or solid state under positive pressure (Göttermann et al., 2016). Generally, the gaseous phase is generated by blowing agents (Khemani, 1997), which produce gases from inert gases such as nitrogen, carbon dioxide, or chemical reactions. Those forming processes with high-volume continuous or semi-continuous production systems are widely applied at the commercial scale.

2.2. Key properties and applications

Several synthetic polymers, namely polyethylene (PE), polypropylene (PP), polyurethane (PU), polyvinyl chloride (PVC), and polystyrene (PS), are common raw materials for foam products. Linear polymers, e.g., PE and PP, due to their symmetric molecular structure, tend to be more crystalized with high mechanical and chemical stability. It can be expanded by controlling its crystallinity (Doroudiani et al., 1996) or blending with other additives and polymers (Laguna-Gutierrez et al., 2018). Foamed, expanded or extruded PS, the aromatic hydrocarbon polymer, is a thermoplastic polymer much favored for its insulating properties as well as its damping properties. It is processed through compounding, mold pressing, foaming, and shaping. Moreover, expanded PVC is produced by polymerization of the vinyl chloride monomers with excellent non-combustibility. By varying, mixing, and reacting as two or more liquid streams referred to as the polyurethane system, PU foam with certain mechanical properties can be formed, particularly the polyols, which come in a great variety from thermoplastic to thermoset materials. The PU foams are characterized by low thermal conductivity and density, exceptional strength, moisture resistance, and light weight. Furthermore, additives consisting of blowing agents, crosslinkers, fillers, and chain extenders are able to improve their performances or give them unique properties (Krämer et al., 2010). The extensive usage of these foam products can be attributed to their many distinct advantages, such as lightness, i.e., reduced weight, buffering/cushioning capacity and heat insulation. Their low compressive strength and high deformation capacity impart excellent properties for absorbing shock and/or impact energy, leading to standalone protective applications in various areas, including construction as thermal insulation panels and packaging as loose-fill chips/trays (Fig. 1). Other applications, including the core materials of sandwich panel, e.g., sport equipment, aircraft, and automotive, are employed as in these cases, both the strength and lightness are highly desirable (Sanami et al., 2014). In general, conventional plastic foams are commonly classified as closed cell and open-cell by the structural morphology of the gas bubbles in the plastic matrix, or by the rigidity as flexible, semi-flexible, semi-rigid, and rigid foams, or by applications as thermal insulation, cushioning, floatation, absorption, structure, acoustic and electrical insulation foams (Chen et al., 2013; Jin et al., 2019; Zhang et al., 2023). Thermosetting rigid closed cell foams have good buoyancy characteristics and thermal insulation properties, while thermoplastic open-cell foams are flexible and have good cushioning and absorbing properties. The general knowledge is that the mechanical properties such as tension, compression, flexion, torsion, and impact properties of conventional plastic foams are closely associated with those of the plastic polymer matrix, the number/size/distribution/structure of the gas bubbles in the matrix, and the temperature of the environment (Saha, et al., 2005; Zhang et al., 2023). Bio-based foams can be produced in a similar way and with similar properties as their plastic counterparts. Table 1 compares the physical properties of some conventional plastic foams and bio-based foams. More details will be discussed on a few selective bio-based foams, including bio-based PU, PLA, starch, PHA, and cellulose foams.

III. BIO-BASED FOAM PRODUCTS

Bio-plastic materials are classified into three groups: firstly, products composed of petroleum-derived sources that possess biodegradability; secondly, bioplastics that lack biodegradability; and finally, bioplastics that are both biodegradable and derived from renewable sources (Fig. 2). The global bioplastics production capacity grows rapidly, however, it is still very limited (Skoczinski et al., 2023). Despite this limitation, given the substantial prevalence of conventional plastics in the market, the share of bio-based materials is anticipated to steadily increase due to the demand for sustainable alternatives.

3.1. Manufacturing processes

Various manufacturing methods of biofoam products are summarized in Table 2. Injection-molding and extrusion are the two most common manufacturing methods for bio-based foam products. Hot pressing is also used for foam production from bio-based PU and cellulose derivatives. Other manufacturing methods include casting and blown film thermorming for PLA, baking/compression for starch, foam forming for cellulose, and steam explosion for cellulose derivatives.

3.2. Bio-based Polyurethane foam

To produce bio-based PU foams, it has been shown that both PU raw materials, polyols and isocyanates, can be obtained from renewable resources, such as vegetable oils and lignocellulosic biomass. Thermolysis or solvolysis process was adopted to liquefy the biomass feedstock with organic solvents, which can produce polyols for the manufacturing of bio-based PU. Vegetable oils and their derivatives, such as palm oil, soybean oil, castor oil, and karanajia oil, are also good raw materials for bio-based PU (Carriço et al., 2016; Poussard et al., 2016; Himabindu et al., 2017; Kormin et al., 2017; Kurańska et al., 2020). Their main components are esters of glycerol with three long-chain fatty acids, having various composition depending on the source of oil. Different modifications were carried out to improve their processability and/or enable the production of different bio-based polyols with distinct properties. Lignin is another source of biopolyols. Globally, there are approximately 50 million tons of lignin produced annually as a by - product from the pulp and paper industry and/or from the biorefinery industry, which is often used as an energy source (Mondal et al., 2020). Technical lignin has a relatively low molecular weight, and it can substitute up to 40 % of the polymer of foam products (Tondi et al., 2016). With a cross-linked aromatic structure containing many phenolic and aliphatic hydroxyl groups, the high- polydispersity lignin is amenable to different functionalization opportunities. Biopolyols produced from lignin are abundantly available and low-cost, rich in reactive functional groups, and require low isocyanate consumption (Ahvazi and Ngo, 2018). The typical production method is shown in Fig. 3. The PUs products incorporated with lignin also demonstrate good thermal stability, enhanced biodegradability and ultraviolet stability (Alinejad et al., 2019).

Polylactic acid foam

Polylactic acid (PLA) is a thermoplastic linear polymer available in amorphous and semi-crystalline forms. Lactic acid, the raw material, can be produced by microbial fermentation of polysaccharides (e.g., potato, sugarcane, and corn) (Datta and Henry, 2006). Also, through ring-opening polymerization of lactic dimers, high molecular weight PLA can be formed (Mehta et al., 2005). It is widely used due to its toxic-free profile and excellent mechanical properties. Expanded PLA foams are mostly made through extrusion, using blowing agents or gas injection, followed by batch foaming processes (Lim et al., 2008). That in turn produces pre-expanded beads, which subsequently can be molded, using heat or steam, into the final product as displayed in Fig. 5. The PLAs have excellent properties, such as a high melting temperature, exceptional mechanical strength, stiffness, and adaptive processing procedure. Their excellent developments in polymer manufacture, modification, or compounding allowed them to achieve a wide range of properties. Moreover, these properties can be tailored by modifying the ratio between the lactic acid monomers and functional additives comprising the PLA. Despite these benefits, there are some challenges and difficulties faced in PLA's applications due to limited processing adaptability. One major problem is that PLA has a low melting strength and slow crystallization kinetics. This makes it hard to make fine-celled PLA foams that are evenly distributed and have a high void fraction (Ameli et al., 2013). In addition, PLAs are brittle, sensitive to moisture and heat, and have low impact resistance, limiting their processing window and applicability (Liu et al., 2018a).

IV. CONCLUSION

In general, the physical properties and performance of bio-based foams are comparable to those of conventional plastic polymer foams. However, the challenges remain in producing bio-based foams for more demanding applications. It is challenging to fabricate resilient flexible bio-based PU foams with lignin-based polyols due to lower reactivity compared with petroleum-based phenols. The PLA has a low melting strength and slow crystallization kinetics, which makes it difficult to produce PLA foams with uniform fine cells, and the resultant PLA foams have low impact strength, and are sensitive to moisture and heat. Starch-based foams are also sensitive to moisture and liquid water, although chemical modifications of the hydroxyl groups of starch and/or blending with natural/synthetic polymers can impart desired hydrophobicity to starch foams. The challenge in PHA foam production is associated with the high thermolysis near the melting temperature of PHA polymer, which narrows the processing window and reducing their melt strength during processing. Cellulose foams are susceptible to water vapour and liquid water due to the hydrophilic nature of cellulose. At high humidity, cellulose foams absorb moisture quickly from the air and expand in dimension; when in contact with water, the mechanical properties of cellulose foams may decrease dramatically. Chemical modification with alkenyl succinic anhydride, alkyl ketene dimer, or isocyanates of the hydroxyl groups of cellulose may increase the hydrophobicity and water resistance of cellulose-based foams. Further research and development are needed to enhance biopolymer processability, decreasing the production cost increasing the water resistance of bio-based foams to meet more demanding applications. For increasing their industry prospect, future research is anticipated to enhance the adaptability, economic competitiveness, and expand their potential applications in various sectors like packaging, thermal insulations, industrial usages (e.g., structures). A vital stride involves researchers collaborating with industrial partners, enabling comprehensive investigation of fundamental understanding, optimization, design, and engineering/cost effectiveness considerations. This collaborative approach will certainly speed up the development and commercialization of many bio foam products that are aligned with the public demand for green and sustainable development.

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