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Protein-based bioplastics for dental applications: Opportunities, challenges, and future directions

Abstract
In dentistry, there is an increasing demand for sustainable, biocompatible materials, coupled with a heightened need for research into promising next-generation bioplastics. Techniques such as crosslinking and blending can modify the properties of these bioplastics, including their biodegradability and moldability. This article examines bioplastics broadly, with a specific emphasis on wheat-based gluten and gelatin bioplastics and the scope of these bioplastics in dentistry. It discusses their fabrication methods, future prospects, limitations in dental applications, and potential strategies for improving their stability in humid oral environments. These materials may eventually be utilized for creating temporary dental prostheses, impression trays, aligners, and scaffolds for regeneration, oral strips, and barrier membranes. However, despite their promising characteristics, issues related to moisture sensitivity and long-term durability pose challenges for their clinical application. Additionally, allergenicity is a concern for certain populations. This paper underscores the need for further research to enhance the suitability of wheat gluten-based and gelatin-based bioplastics for application in dentistry.

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INTRODUCTION

Plastics are synthesized from petroleum products such as oil, natural gas, or coal. The process initially includes fossil fuel extraction followed by conversion of the fuel into monomers.[1] This step is subsequently followed by the polymerization of monomers into resin. The entire process of fuel extraction, monomer production, polymer creation, and plastic production poses significant environmental concerns because of the release of harmful substances.[1,2] On the other hand, the manufactured plastic is non-biodegradable, further intensifying the contamination of air, water, and soil.[1,2] As plastic manufacture affects the ecosystem, there is a pressing need to reduce the dependence on petroleum products and redirect our research to alternative energy sources.

In dentistry, polymethyl methacrylate, an acrylic resin, is a petroleum-derived product used in the fabrication of prostheses.[3] It is extensively used, as it is affordable and has ease in manipulation with desired physical properties. Similar to plastics, the production, utilization, and disposal of acrylic resin contribute to environmental pollution.[4] Additionally, acrylic resins release residual monomers that are potentially toxic to both humans and the environment.[4-6] Therefore, there is an increasing need for research to explore alternatives to dental acrylics that are both biocompatible and safe.

BIOPLASTICS

Bioplastics are innovative polymers that provide an eco-friendly substitute for the conventional petroleum-derived plastics.[7] According to European Bioplastics, these are either bio-based, biodegradable, or both. The term 'biobased' refers to materials that are derived from biomass, which includes renewable organic materials sourced from plants and animals.[7,8] Mostly, the primary feed stocks are crops such as rice, corn, sugarcane, cellulose, potato, maize, wheat, and various forms of natural, renewable sources, instead of petroleum products. Thus, these bio-based bioplastics decrease carbon emissions by reducing dependence on fossil fuels. On the other hand, biodegradation is a chemical process where the microorganisms in the environment break down the plastic into water, carbon dioxide, and compost.[7-9] As it is a natural process, the time taken to biodegrade depends on surrounding environmental conditions and the properties of the material. On the whole, bioplastics, because of their source of production or their biodegradability, enhance sustainability across numerous applications, including the biomedical field. As biodegradability is an add-on property of certain types of bioplastics, there is a need to strive for the development of materials that are both bio-based and biodegradable so as to offer environmentally friendly alternatives.

The bio-based biodegradable plastics are of various types, like polylactic acid, polyhydroxyalkanoates, starch blends, cellulose-based plastics, and lignin-based polymer composites. Additionally, polybutylene adipate terephthalate and polycaprolactone are additional biodegradable bio-based ones as mentioned in the classification. All these are made from renewable sources like plants, animal products, and microorganisms, which degrade through microbial activity, thus mitigating plastic pollution by finding application in packaging, agriculture, and biomedical devices.[7-9]

Based on the material from which these bioplastics originate, these can be classified as starch-based, cellulose-based, protein-based, bio-derived polyethylene, and aliphatic polyesters. Despite being biodegradable and biobased, protein-based bioplastics have to overcome their limitations to find potentially useful applications.[10-11] There is a need to address issues such as mechanical problems, water sensitivity, high production costs, and limited industrial production. This field can be an active developing area of research aiming to improve the properties through additives, hydrophobic modifications, and cross-linking, as these can be used for specific applications, including biomedical ones.

PROTEIN-BASED BIOPLASTICS

Protein-based bioplastics are made from natural protein sources such as plant products or animals. These are a long-lasting replacement for plastics made from petroleum products. Wet or dry processing technologies, such as casting, extrusion, and molding, are used to make these bioplastics. Plasticizers are often used to make them more flexible and stronger. They are derived from nature, have antimicrobial properties, and can be composted.[10-13]

Protein-starch blended bioplastics [14]

Protein-starch combined bioplastics blend starch from sources such as potato, corn, cassava, or sago with proteins such as gelatin, gluten, or albumin. These bends can address some limitations such as water sensitivity and brittleness of starch bioplastics through hydrogen bonding and compatibilization. Starch alone is brittle, and adding proteins can add strength and flexibility. The resulting blend leads to better tensile strength and elasticity, producing more useful bioplastic. As both starch and proteins are biodegradable, the material breaks down easily in soil and compost. Along with this, both the materials are derived from renewable agricultural resources, thus reducing the carbon footprint. Starch is highly water-sensitive, and blending with proteins can reduce the moisture absorption, thus improving the durability of the material. Along with this, starch is cheap, which lowers the overall material cost, and this blend can avoid expensive synthetic additives.

WHEAT GLUTEN-BASED BIOPLASTICS

Bioplastics derived specifically from wheat gluten are environmentally sustainable and decompose spontaneously. Starch and bioethanol industries provide wheat gluten as a byproduct, which can be used for bioplastic production. Bioplastics derived from wheat gluten possess distinctive viscoelastic and thermoplastic characteristics, exhibit oxygen barrier capabilities, and are non-toxic. Bioplastics derived from wheat gluten decompose spontaneously in soil or compost within weeks, rendering them environmentally beneficial like other protein-based bioplastics.[15-18]

Fabrication of wheat gluten bioplastics—Methods

The specific fabrication methods for gluten-wheat-based bioplastics are not well documented in literature. However, several methods for fabricating dental acrylics can be combined with those used for bioplastics and tested. The first method is the dough method, where the gluten powder can be mixed with a suitable liquid, hand molded for the desired shape, and controlled and dried under consistent pressure. These bioplastics can also be fabricated using thermoplastic processing methods like extrusion or compression molding. The latest emerging techniques of additive manufacturing, like 3D printing, can also be tried for precise control over the process.[18-20]

Future prospects for wheat gluten bioplastics

In the future, wheat gluten bioplastics can have several potential dental applications because of properties like biocompatibility, biodegradability, and film-forming abilities.[20] The material can be molded for the fabrication of temporary dental prostheses, impression trays, impression materials, aligners, and scaffolds in regenerative procedures, oral strips, and barrier membranes. These bioplastics can also be employed for the fabrication of dental and packing materials. Thus, these materials can be used as replacements for petroleum-based plastics in situations where the material is intended for short-term use or is frequently replaced or as replacements for disposable products that contribute significantly to plastic waste. These can also have potential application in oral hygiene routines, which include toothbrushes, floss, floss picks, and dental bibs. Thus, the devices and materials fabricated using these bioplastics stand out as biodegradable alternatives and reduce the environmental impact while maintaining the dental care quality.

Limitations of wheat gluten bioplastic usage in dentistry

The major limitation of wheat gluten-based bioplastics is the sensitivity to heat and moisture.[15-19] Excessive temperature and moisture can cause material degradation and loss of mechanical integrity by altering its properties. The water permeability and moisture sensitivity can cause swelling, hydrolysis, and degradation of wheat bioplastics. The possibility of sterilizing the material is a problem, as the elevated temperature exposure can reduce the adhesion properties in the composites, which in turn induces aging and loss of mechanical properties and embrittlement. Even other modes of sterilization, like chemical and radiation, can also impose problems like the release of toxic residues and impact mechanical properties due to damage from protein crosslinking. Another limitation is the natural attraction of fungal growth on these bioplastics. The fungal growth weakens the material and limits the long-term stability.

Enhancement of wheat gluten bioplastic properties[15-20]

The mechanical strength, water resistance, and thermal stability of wheat gluten-based bioplastics can be enhanced by the incorporation of various substances. The addition of natural fibers such as flax, hemp, or carbon into wheat gluten enhances the formation of hydrogen bonds between the fibers. The incorporation of hydrophobic substances such as castor oil, silicone oil, and hydrophobic polymers such as polyvinyl alcohol or polylactic acid enhances the water resistance and elevates the degradation temperature, thus preventing the premature breakdown. Other factors like extrusion temperature, compression molding, and usage of plasticizers like glycerol further enhance the protein crosslinking, elasticity, and water barrier properties. Further, the genetic modification of gluten proteins and the combination of these with synthetic polymers can enhance the production of compatible and durable bioplastics, which can be used in varying conditions. To reduce fungal growth, materials such as gallic acid can be added to the bioplastic.

GELATIN-BASED BIOPLASTICS

Gelatin-based bioplastics are primarily derived from either animal-based or plant-based sources. Animal-based gelatin is derived from the connective tissues of animals such as pigs, cattle, fish, and poultry byproducts, whereas plant-based gelatin is derived from various plant sources such as seaweed, fruits, and root vegetables. The gelatin is combined with plasticizers such as glycerol and additives such as acetic acid or vinegar to improve the mechanical properties and processability. Gelatin provides the primary gelling function, whereas glycerol modulates the texture, durability, and biodegradation characteristics of bioplastics. Further, by incorporating other materials into the bioplastic, its properties can be tailored for specific applications.[21-23]

Fabrication of gelatin-based bioplastics—Methods

The fabrication of gelatin-based bioplastics involves a series of steps. First, the gelatin powder is dissolved in water, followed by gentle heating to solubilize the protein, then the incorporation of plasticizers and additives. The solution can then be poured into molds and allowed to set and dry at a slightly elevated temperature to form the bioplastic. The drying process ranges from several hours to days depending on thickness and humidity. The resultant plastic is suitable for packaging as well as biomedical applications. The choice of additives influences the transparency, strength properties, biodegradability, and resistance to moisture.[21-26]

Future prospects for gelatin-based bioplastics

Gelatin-based bioplastics have a significant future in dentistry, particularly in the fields of regenerative therapies, tissue engineering, and drug delivery.[27-31] The development of gelatin methacryloyl hydrogels has been used to support dental cell growth and tissue regeneration due to their excellent biocompatibility and ability to mimic the properties of the extracellular matrix. Thus, these act as scaffolds for regeneration, injectable carriers for drug delivery, and as membranes for bone augmentation procedures. Ongoing research to increase the functionality and practicality of gelatin-based bioplastics by chemical crosslinking and nanocomposite integration projects this material as a sustainable dental biomaterial.[27-31] Research is required not only in this field, but also to expand the use of these bioplastics in dentistry by addressing their limitations.

Limitations of gelatin-bioplastic usage in dentistry

Gelatin-based bioplastics have certain limitations that restrict their broader utility in dentistry. The major limitation of these bioplastics is the poor mechanical strength, as these are susceptible to deformation under load, which makes them unsuitable as restorations or as load-bearing prostheses. Another major drawback is the rapid degradation of the material in moist or enzymatic conditions, which makes it unsuitable in the oral cavity. The material is water absorbent and is prone to swelling when exposed to saliva and other oral fluids. These properties can hinder the usage of this material in impression materials or temporary prostheses. The material is also having thermostability issues, posing a challenge for intraoral application.[32-34]

Enhancement of gelatin based bioplastic properties[35-38]
To overcome these limitations, composite materials can be tested by blending the gelatin with various materials. Polysaccharide blends like agarose and starch can increase the mechanical durability, hardness, and thermal stability, whereas blending gelatin with chitosan can enhance the antimicrobial properties and mechanical performance. Gelatin can also be blended with collagen to improve the mechanical and thermal properties. It can also be mixed with substances like ceramics or synthetic polymers. The chemical modification and formation of photocrosslinkable gelatin methacryloyl, along with genipin crosslinking, can enhance the mechanical properties and regulate the degradation process. However, these procedures can increase production costs and may also raise toxicity levels. The plasticizer content can also be controlled and regulated to mold the properties of the material.

DISCUSSION

In dentistry, the environmental burden caused by petroleum products has prompted the research to explore biodegradable and sustainable alternatives. Bioplastics derived from gluten and gelatin have the potency to emerge as a promising material for various dental applications, especially those intended for short-term or disposable purposes.[30] From a dental point of view, these can minimize the waste without compromising the patient safety. Wheat gluten is suitable for temporary prostheses and impression trays. These decompose in soil/compost within weeks, thus supporting sustainability in high-turnover dental clinics. However, moisture sensitivity is the major clinical challenge, as the oral environment can induce swelling and hydrolysis of the material that can risk the dimensional stability of the material.[15-19] Problems with sterilization pose a problem for reusing the material, and fungal susceptibility is a major concern for chair-side use. On the other hand, gelatin can have a role in tissue engineering by acting as a scaffold for the regeneration of pulp, periodontium, and bone.[27-31] The main advantage of this is the possibility of fabricating this bioplastic with a simple fabrication method. However, poor mechanical strength and rapid enzymatic degradation are the drawbacks for expanding the usage of this material in dentistry.

The usage of additives can reduce the drawbacks and bridge the gap by enhancing the properties of these materials. Hydrophobic additives like castor oil, polylactic acid, and hemp fibers improve water resistance and tensile strength of gluten bioplastics. Additionally, glycerol plasticization can enhance elasticity, and gallic acid addition can improve the anti-fungal properties of the material. Whereas, gelatin benefits from chitosan addition, and genipin slows degradation. Both these properties help in tailoring the resorption of the scaffold. Protein-starch combined bioplastics can address some of the limitations of both the materials.

Many regulatory hurdles, such as biocompatibility testing and sterilization validation, require crossing. There is a need to conduct in vitro studies on the material properties of these bioplastics, later followed by randomized clinical trials on oral performance, microbial adhesion on these materials, and accuracy.

Apart from oral use, these bioplastics can be employed as a replacement for single-use plastics used in dental clinics. In practice, dental clinics generate substantial single-use plastic waste from routine procedures, which is reported to be an average of 21 items (354 grams) per patient. These include barriers, trays, bibs, cups, suction tips, and personal protection equipment packaging. Replacing these items with protein/starch bioplastics or a combination (gelatin or wheat gluten blends) promotes green dentistry by reducing the landfill contribution and carbon dioxide emissions up to 27 kg weekly per practice.[39]

CONCLUSION

Wheat gluten bioplastics present a promising future advanced sustainable dental material. The desirable properties like renewability, non-toxicity, and biodegradability make this material a future possibility. To improve the properties and expand their usage in dentistry, the formulations can be optimized by crosslinking and through nanostructural arrangements. On the other hand, gelatin-based bioplastics hold promise for tissue regeneration, wound healing, and use as scaffolds. However, the mechanical, chemical, and thermal limitations constrain the applicability of this material for load-bearing prostheses in the oral cavity. Both types can offer a distinct advantage over conventional petrochemical-based plastics by reducing the environmental impact. However, there is a need for continuous research to optimize these bioplastics for dental applications and resolve the material limitations. Interdisciplinary collaboration can contribute to green dentistry and reduce the plastic waste from the health care sector.

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