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Production of sustainable bioplastics for food packaging derived from natural sources

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Abstract

Petroleum-based polymers have been used for many years in various products and applications. The main disadvantage of these polymers, though, is their detrimental effects on the environment. When these plastics are not properly disposed of, they eventually affect people. The increasing demand for plastics worldwide and the ensuing ecological damage need the development of an efficient, ecologically acceptable alternative, such as bioplastics or biodegradable polymers. Utilizing biodegradable materials derived from natural polysaccharides, especially starch helps in lowering the use of non-biodegradable resources. In this paper, we provide a literature survey on food packaging, bioplastics and its classification, and the application of starch and its modification methods. Herein, in this study, we focused on the environmentally friendly production of bioplastic samples derived from corn starch which can be utilized as food packaging.

Key Words:

Bioplastics; Polysaccharides; Starch; Food packaging; Biodegradable

1. Introduction

Food packaging has developed significantly, primarily due to the increasing concerns about food waste and environmental sustainability. Food packaging plays a notable role in maintaining and enhancing food quality during distribution, storage, and transit (Duda-Chodak et al., 2023). A necessary component of the food industry, food packaging uses petroleum-based plastics and addresses the preservation and protection of all food varieties. The use of petrochemical–based plastics, including polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), polyamide (PA), and polystyrene (PS), (Jang et al., 2020; de Oliveira et al., 2021; Behera et al., 2022) as packaging materials has increased due to their high availability at relatively low cost, good mechanical performance, including tear and tensile strength, and good barrier to carbon dioxide, oxygen, anhydride, and aroma compounds (Sadeghizadeh–Yazdi et al., 2019). There are health and environmental risks associated with the growing usage of plastics derived from petroleum. Because of their complete nonbiodegradability, they also have an adverse effect on the health of employees who clean or maintain the processing equipment, which has resulted in major ecological issues (Onyeaka et al., 2022).

Bioplastics have emerged as a potential key to the environmental effect of conventional plastics. Interest in the creation of "bioplastics," or packaging materials that not only function better but are also simple to recycle and reuse, has increased as a result of the growing environmental concerns brought on by the excessive accumulation of plastic (Kong et al., 2023; Li et al., 2024). According to the European Bioplastics organization, bioplastics can be classified as either biobased (produced from renewable resources) or biodegradable (manufactured from polymers that can be composted or decomposed). Maize starch, potato starch, fibers from pineapple, jute, hemp, henequen leaves, Vegetable oil, and banana stems, as well as leftover plastic bottles and other containers, are among the renewable materials that are used to create bioplastics using microorganisms (Mangaraj et al., 2019). Under the right circumstances of temperature, moisture, and oxygen or biomass, biodegradable polymers can break down primarily by the enzymatic action of microorganisms to produce CO_2, CH_4, H_2O, and inorganic chemicals (Kringel et al., 2020). Thus, biodegradable packaging materials are those that are broken down by naturally existing organisms such as bacteria, yeast, or fungus (Tesfaye et al., 2018). These materials may be composted and used as fertilizer or humus (Yadav et al., 2021). Nevertheless, not all bio–based plastics are biodegradable, and vice versa (Iacovidou et al., 2018).

Although there are differences in how bioplastics are classified, one popular method separates them into three categories: microbial–derived polymers, synthetic bio–based polymers, and natural polymers (such as chitosan, cellulose, and starch) (Avérous & Pollet, 2012). Because of its availability, low cost, and complete biodegradability, starch–based packaging has drawn a lot of interest among these (Maniglia et al., 2021, Kowser et al., 2025).

According to Zia-ud-Din et al. (2017), starch is the second biggest renewable material after cellulose and acts as a store of energy in plants. Notwithstanding its benefits, native starch has drawbacks including poor mechanical qualities and moisture sensitivity. Techniques for modification, including chemical, enzymatic, and physical alterations, are used to solve these problems. It has been discovered that dual modification approaches improve starch's resistance to enzymatic degradation and structural stability (Ashogbon, 2021; Mathew et al., 2025). Furthermore, research indicates that annealing and ultrasonication together might change the hydrogen bonds in starch, enhancing its functional qualities (Amarnath et al., 2023). These developments raise the possibility that polymers based on starch might replace conventional plastics in food packaging.

Considering the above benefits of starch, in this study starch was selected as renewable material from organic agricultural sources to produce environmentally friendly food packaging materials, accordingly, starch-based bioplastic films were produced by simple and efficient method. Utilizing abundant, biodegradable, renewable, and widely accessible natural substances as reinforcing fillers can help reduce the dangers and issues related to conventional plastics.

2. The Theoretical Framework

1-Food packaging:

From product packaging to consumption, food packaging carries out several tasks, such as preserving and enhancing food quality during distribution, storage, and transit (Han et al., 2018). Food waste is also connected to the function of packaging. Post-harvest and processing losses account for over 40% of the world's total produce, or 1.3 billion tons of food waste annually, particularly in low-income nations (Coll & Kleineidam, 2020). About 40% of the produce produced in India is wasted, making it a major food producer (Kumar et al., 2020; Mor et al., 2018). However, conventional package design is responsible for roughly 20–25% of global residential food waste (Williams et al., 2012). Paper, metal, glass, and petrochemical plastic polymers are examples of conventional materials used in food packaging. A decrease in the production of nonbiodegradable plastics was seen, and by 2019, 56% of packaging was biodegradable (Ncube et al., 2020). By 2025, the EU Commission hopes to have 55% of plastic packaging recycled, and by 2030, all plastics will be recyclable or reusable thanks to the circular economy strategy (García-Guzmán et al., 2022). According to recent reports, biodegradable packaging accounts for a substantial component of bioplastic market (1.14 million tonnes, 53%), particularly in the food packaging sector (Ncube et al., 2020; Shaikh et al., 2021). More focus has been placed on creating biobased materials, particularly for packaging, as a result of requests to reduce

the use of synthetic plastics and the rise in global temperatures brought on by climate change (Wei et al., 2024).

2-Plastic materials:

A detailed examination of plastic materials reveals that this material group includes a variety of polymers with varying qualities, including polyolefins like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). As a result, they also provide a variety of benefits and drawbacks. Since plastics are lightweight, formable, inexpensive, versatile, and controllable (mechanical, physical, and chemical properties, barrier, color, temperature stability, and sealability), convenient (transportability and resistance to breakage), and useful for creating multilayer materials, it can be said that they are frequently chosen for packaging applications (Robertson 2009; Soroka 2002). With its extensive effects affecting every aspect of the ecosystem, petrochemical plastic pollution has grown into a global environmental problem that cannot be disregarded (Kim et al., 2023). A startling "plastic siege" is created when large amounts of waste plastics build up in the land, sea, and atmosphere due to their inability to decompose naturally (Ali et al., 2023; Sokolova et al., 2023). Waste plastics are a major hazard to human health and biodiversity because they make their way up the food chain. For instance, human blood has been discovered to contain microplastic particles (Sharma et al., 2022), and plasticizers can lead to disorders of the endocrine system (Bernard et al., 2023). Researchers are increasingly concentrating on naturally occurring biodegradable substances including chitosan (Zhang et al., 2024; Fu et al., 2023), cellulose (Zhou et al., 2024; Pritchard et al., 2022), and starch (He et al., 2020; Versino et al., 2018). To address the present plastic pollution issue and reach carbon neutrality, eco-friendly materials must be developed immediately (Geyer et al., 2017). One type of natural polysaccharide that has garnered a lot of interest and research in recent years is starch (St) (Yuan et al., 2022). Starch is a great option for creating environmentally friendly and sustainable products because of its special physicochemical characteristics, which include low cost, a variety of sources, and strong biodegradability (Xie et al., 2024; Lin et al., 2024). One of the issues facing our society is reducing the use of durable, non-biodegradable packaging materials like glass, metal, and primarily plastic. Research into potential alternatives with suitable packaging qualities is ongoing, and the development of new environmentally friendly packaging solutions can aid in reducing these wastes (Pritchard et al., 2022).

3-Definition of bioplastics:

The European Bioplastics Organization (EBO) states that the term "bioplastics" encompasses plastic's bio-based origin as well as its biodegradable nature (Figure 1) (Teixeira et al., 2023). The 2014 European Standard EN 16575 defines bio-based plastics as those made from plant-based resources, or biomass (Iacovidou et al., 2018; Cruz et al., 2022). Nevertheless, not all bio-based

polymers are biodegradable, nor are bio–based plastics the only ones that are (Iacovidou et al., 2018).

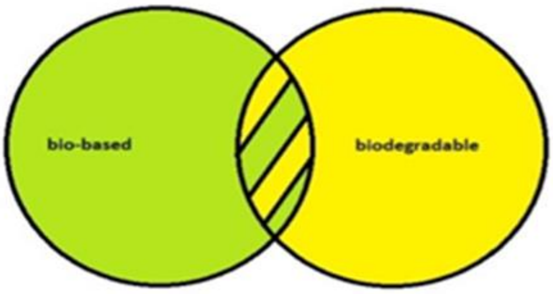

Figure 1: Bioplastics are bio–based, biodegradable, or both (adapted from European Bioplastics)

4–Classification of bioplastics:

Bioplastics can be classified using a variety of criteria, and it is challenging to limit them to a single class. Nevertheless, one classification system based on their origin (Fig. 2) separates these bioplastics into three main categories/types: polymers derived from biomass (natural polymers); polymers chemically synthesized from renewable sources (synthetic polymers); polymers derived from microorganisms (microbial polymers) (Wang et al., 2020).

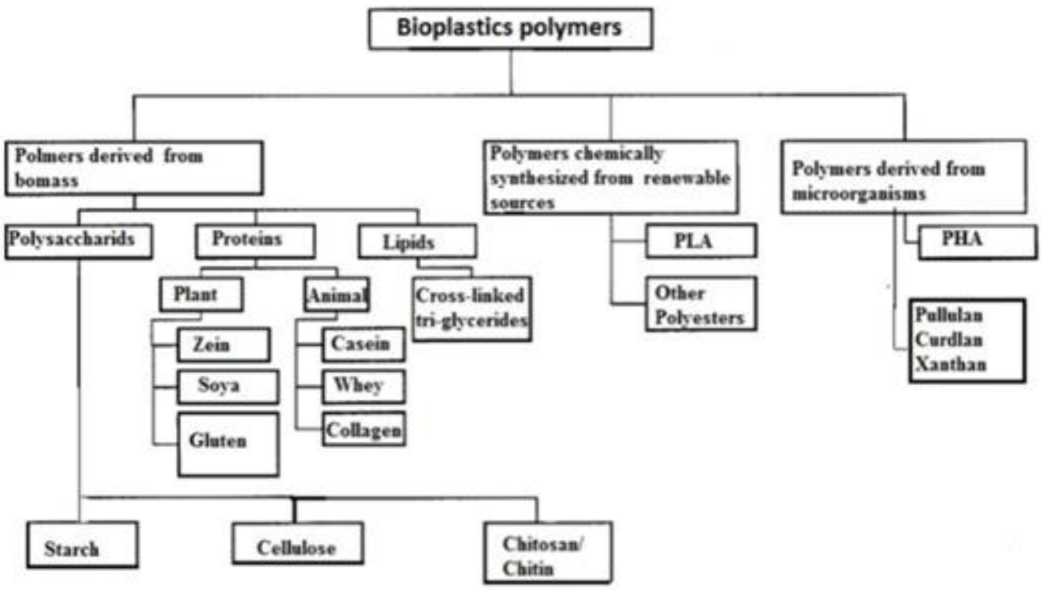

Figure 2: Classification of bioplastic polymers based on origin.

4.1 .polymers derived from biomass:

Polymers that are naturally occurring or that come from biomass animal, marine, and agricultural sources provide natural polymers, which include lipids like cross–linked triglycerides, proteins like plant–derived proteins (zein, gluten, soy, etc.), and animal–extracted proteins (casein, collagen, gelatin, etc.), and polysaccharides like cellulose, starch, gums, chitosan, etc. The majority of these polymers are crystalline and hydrophilic by nature, which causes several issues when processing moist food packaging. However, they are suitable for use in food packaging due to their superior gas barrier qualities (Averous & Pollet, 2012).

Starch

The most widely used renewable raw material and readily biodegradable natural resource is starch. According to Whistler and BeMiller (2007), it can be obtained from seeds, corn, wheat, rice, potatoes, sweet potatoes, and cassava. Starch is a common thermoplastic that can be used in place of polystyrene (PS). It undergoes destructuration in the presence of heat and particular concentrations of water or plasticizers (sorbitol, glycerol), and it is subsequently extruded to plasticize it. Due to its affordable price, starch is a desirable material for packaging applications. The usage of starches is limited by their weak mechanical properties and low resistance to moisture. Thus, starch is combined with different biopolymers and certain additives to enhance these qualities (Yadav et al., 2018).

Cellulose

The most prevalent natural polymer is cellulose, which is produced by delignifying cotton linters or wood pulp. Because it is crystalline and hydrophilic and has poor mechanical qualities when raw, cellulose is exceedingly challenging to utilize in packaging. To create cellophane with superior mechanical properties, it must be treated with chemicals such as NaOH, H2SO4, CS2, etc. (Majid et al., 2018). It is possible to derivatize cellulose from its solvated state by etherifying or exercising the hydroxyl group, which yields cellulose derivatives. For films or edible coatings, cellulose derivatives such as hydroxypropyl cellulose, hydroxypropyl methylcellulose, carboxymethyl cellulose, or methyl cellulose are utilized (Majid et al., 2018). One way to improve the moisture barrier is to add hydrophobic substances, like fatty acids, to the cellulose ether matrix to create a composite film (Morillon et al., 2002).

Chitosan or chitin

After cellulose, chitosan, often known as chitin, is the second most abundant polysaccharide resource in nature. It naturally occurs in the cell walls of yeasts and fungi as well as in the exoskeleton of arthropods. It is made commercially from the waste of prawns and crabs using chemical extraction techniques. Deacetylation of chitin yields chitosan, and various parameters (such as alkali concentration, incubation duration, and chitin toIts characteristics can be influenced by alkali, temperature, and the source of chitin (Thakur & Thakur, 2016). Chitosan reduces oxidation and improves the shelf life and quality of food products by forming films without the need for additives, exhibiting good carbon dioxide and oxygen permeability, as well as excellent mechanical and antimicrobial properties (Gemili et al., 2009)

Proteins

Animal (casein, whey, keratin, gelatine, etc.) and plant (wheat gluten, corn, zein, soy protein, etc.) sources can provide proteins, which are complex structures composed of amino acids. Because they have a special side chain in their structure, they are very useful for changing the necessary properties of packing materials. Proteins and protein-based materials are used in many industrial applications because of their high gas barrier qualities, biodegradability, and renewable nature. However, like starch-based polymers, they suffer from their hydrophilic nature. Consequently, they must be chemically or microbiologically altered, or combined with other polymers (Majid et al., 2018). When handled with the right plasticizers at temperatures between 80 and 100 degrees Celsius, Casein, a protein produced from milk, forms polymers with mechanical properties that range from stiff and brittle to flexible and robust. Casein films appear to be opaque. Because of its superior adhesive qualities, it is still used for bottle labelling today despite its comparatively expensive cost. Under some circumstances, gluten plastics have high gloss and exceptional moisture resistance. They absorb some water when submerged, but they do not disintegrate in it. Studies on gluten's application in edible films, adhesives, Due to its abundance and low cost, it is currently being used for thermoplastic applications (Otles & Otles, 2004). Commercially available forms of soy proteins include soy flour, soy concentrate, and soy isolate. Packaging sheets that are both edible and biodegradable can be made with soy protein isolate (SPI). The performance of the films acquired from SPI is restricted due to their extreme friability. They must be altered by adding a plasticizer, like glycerol, to make them better (Kokoszka et al., 2010). Keratin, the least expensive protein, is taken from waste materials like hair, nails, and feathers. Because of its structure and high cysteine group content, keratin is the most challenging protein to digest (Shukla, 1992). However, whey proteins byproducts of the cheese industry are used extensively as coatings and edible films. In order to enhance the films' moisture barrier qualities, a number of lipid components, including fatty acids, natural waxes, resins, and vegetable oils, are typically added to provide hydrophobicity.

4.2. Synthetic polymers or bioplastics chemically synthesized from renewable sources

They are created using biobased monomers and traditional chemical synthesis. Polylactic acid (PLA) is one of the most widely used and commercially accessible bioplastics in this class.

Polylactic acid (PLA)

One of the most promising and biodegradable polyesters for commercial applications is PLA, which is derived from renewable resources including corn, sugar beetroots, and potato starch and can replace high density polythene. (HDPE), polystyrene (PS), low density polythene (LDPE), and polythene terephthalate (PET). Corn or other carbohydrate sources are converted to dextrose, which is then fermented to produce lactic acid. PLA pellets are produced by either ring-opening polymerization of lactide or direct polycondensation of lactic acid monomers. This transparent material has a wide range of processing options, including blow moulding, thermoforming,

injection moulding, and extrusion overcast film extrusion (Rasal et al., 2010). Because PLA was discovered to perform better than synthetic plastic materials in many situations, it is quickly emerging as a green food packaging material (Auras, 2005). PLA is available in a variety of forms, including films, thermoformed trays and cups, paper and board coatings, and containers.

4.3. Microbial polymers or polymers derived from microorganisms.

This category comprises microbial polysaccharides like pullulan, curdlan, and xanthan as well as polymers like polyhydroxyalkanoates (PHA), PHB, and others that are produced through the microbial fermentation of polysaccharides. This is a relatively new and inventive field with enormous industrial potential.

Polyhydroxyalkanoates (PHAs)

With a melting point of roughly 180 °C, polyhydroxyalkanoates (PHAs) are thermoplastic, biodegradable, biocompatible, and thermostable. These polymers are naturally created when bacteria ferment plant-based feedstocks like sugars or lipids, and they are subsequently extracted using solvents like methylene chloride, chloroform, or propylene chloride. Excellent packaging films are produced using these polymers either by itself or in conjunction with starch or synthetic plastic (Tharanathan, 2003). The most prevalent kind of PHA among the more than 100 PHA composites is PHB, which is made by polymerizing 3-hydroxybutyrate monomer, which has characteristics like PP but is stiffer and brittle. It breaks down into CO_2 and H_2O in both aerobic and anaerobic environments. PHB possesses high gas barrier qualities and is optically active in addition to being insoluble in water (Castilho et al., 2009). Because of their comparable chemical and physical characteristics, PHAs have the potential to replace a wide range of traditional polymers. PHAs' uses in the food industry are further enhanced by their printability, flavour and odour barrier, heat sealability, resistance to grease and oil, temperature stability, and ease of dyeing (Tripathi et al., 2014). Using a variety of microbial polysaccharides as a packaging film, including xanthan, pullulan, curdlan, and others, is a novel idea that requires biotechnological methods. The yeast-like fungus Aureobasidium pullulans produces pullulan from substrates that comprise linear, water-soluble, and exopolysaccharide (EPS) sugars. It is used for packaging in a number of sectors, including cosmetics, food, and medicine. Films made of pullulan are edible, uniform, translucent, printable, heat-sealable, flexible, and have an excellent oxygen barrier. They are also nontoxic, tasteless, odorless, and biodegradable. Pullulan membranes are especially appropriate for food applications because they prevent the growth of fungi (Freitas et al., 2014). Agrobacterium bio bar and Agrobacterium tumefaciens generate curdlan, a bacterial polysaccharide that is mostly utilized in the food sector as a gelling agent. but has a great deal of untapped potential for the creation of packaging films.

Conversely, Xanthan is a highly viscous, water-soluble, and harmless substance that is created by the aerobic fermentation of Xanthomonas campestris using sucrose or glucose as its primary carbon source. The information regarding xanthan's potential in the packaging industry is scarce. The high cost of manufacture could be the cause of this. Nevertheless, acerola that was coated with xanthan showed less weight loss and respiration, preserving its colour and lengthening its shelf life (Quoc et al., 2015).

5-Using starch in food packaging :

Polymeric carbohydrate starch is made up of polysaccharides which are compounds produced from the polymerization of glucose molecules (Gutiérrez & Bello-Pérez., 2022). With a typical particle size distribution of 1–100 µm, starch is found in higher plants in a variety of granular forms and is the second biggest renewable substance after cellulose (Zia-ud-Din et al., 2017). Consequently, starch has gained international attention, especially due to its accessibility, affordability, and full degradability (Maniglia et al., 2021). Why Make Use of Starch in Packaging? A variety of green materials are made from starch as a beginning element. Polysaccharides make up 75% of the earth's total organic matter. Starch is a significant carbohydrate. Starch is produced by plants and stored in their structures as a source of energy. Plant roots and tubers, as well as seeds, contain starch. Corn is the primary source of starch produced globally (Asaf Kleopas, 2008).

6 -Starch modification methods:

Two methods for altering starch are a promising method for achieving high amylose starches and changing the physiochemical properties of NS. Route is to use dual modification techniques. In a twofold modification of starch, the granular surfaces are usually prepared using the first modification. The second modification then concentrates on fortifying the linkages inside the starch chains. Dual modification can be broadly divided into two types: homogeneous dual modification and heterogeneous dual modification. Several enzymatic, chemical, and physical modifications Cations are subject to homogenous changes. Heterogeneous modification types include dual modification mechanisms that are chemical/physical, chemical/enzymatic, or the opposite (Ashogbon, 2021). High amylose starch and increased gela-resistance to enzyme digestibility, crystallinity, and thermal stability were the outcomes of extrusion and heat moisture treatment of maize starch (Yan et al., 2019). By generating structural and functional rearrangement, the combined advantages of dry heating and annealing altered the starch's molar mass and amylose-amylopectin ratio. It resulted in a high pasting temperature and stable starch. Additionally, twofold modification reduced enzymatic digestibility. due to elevated levels of RS (Chi et al., 2019). Together, annealing and ultrasonication alter intra- and inter-hydrogen bonds and the reassociation of the amylose and amylopectin chains in millet starch. Consequently, RS levels rose by 31–33% and the body's ability to absorb water was reduced (Amarnath et al., 2023).

3.Methods of Research and the tools used

Materials:

Corn starch was purchased from local market. Acetic acid (vinegar) with a 5% concentration and glycerin (Plasticizer) were collected from the commercial market. Distilled water was collected from the chemistry lab in faculty of Education-Ain Shams University.

Tools:

Glass beaker, stirring spoon, Heat source (hot plate or stove), Mold or flaring surface for casting

Bioplastic sample preparation:

The film (corn-based bioplastic) solution was prepared by mixing 70 ml of distilled water and 10 gm of corn starch. The mixture is stirred well to ensure even distribution. Then, 5 ml of vinegar (5% concentration) is added, followed by 5 ml of glycerol, which helps improve the flexibility of the final material. Vinegar was used to break some of the polymer branches of amylopectin. A heavily branched polymer hinders the formation of good plastic. Once the mixture is prepared, it is heated in a water bath under constant stirring. As the heating progresses, the mixture thickens and becomes more viscous and translucent. The resulting solution was poured into a mold or spread onto a flat surface, that acted as a casting plate and dried in air for 72 h, to ensure consistent film thickness (Nasir & Othman, 2021; Kowser et al., 2025; Cristofoli et al., 2023). A diagram of experimental procedure of bioplastic synthesis is disclosed in Figure 3.

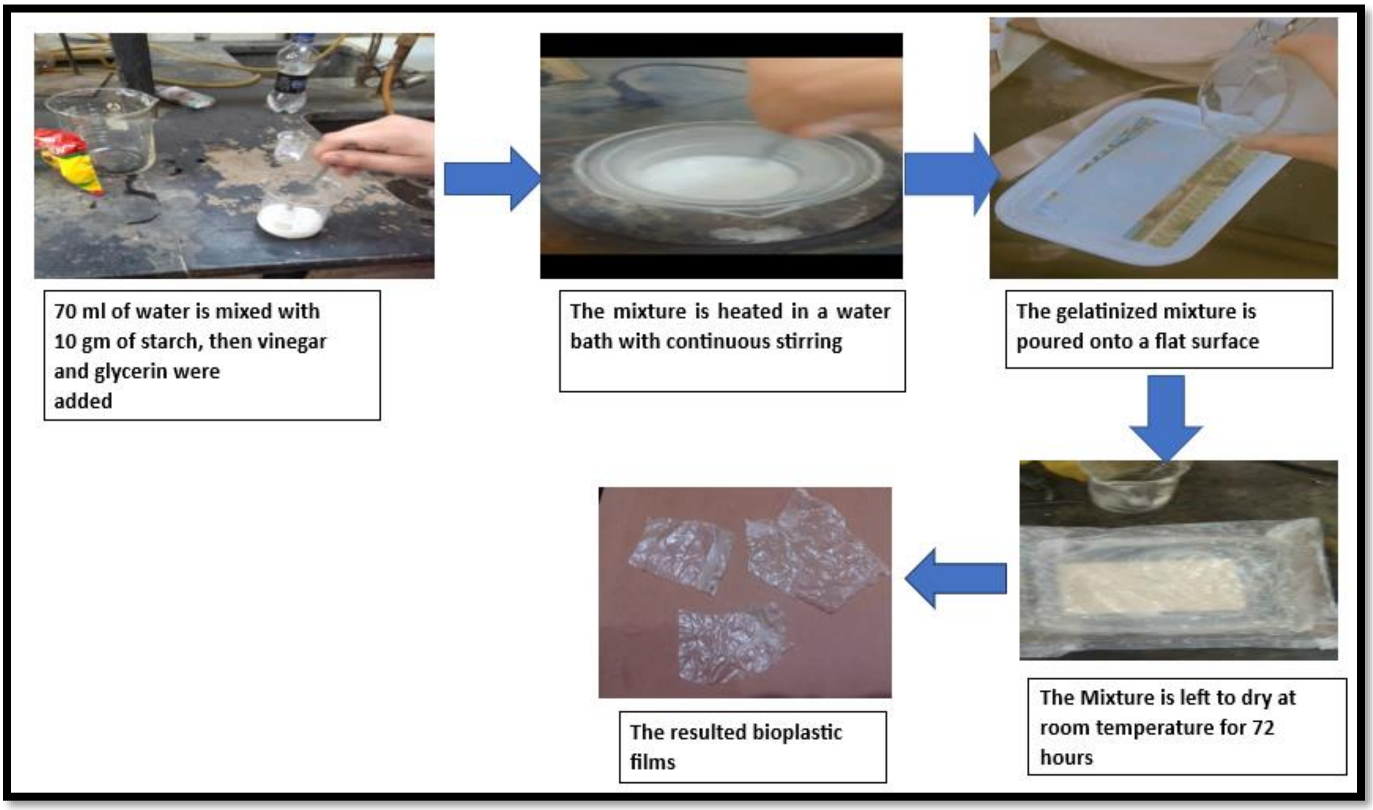

Figure (3): Experimental procedure of bioplastic synthesis

4. Results of Research and Interpretation of Results

Bioplastics have become an environmentally beneficial substitute for traditional plastics that are not biodegradable, as a result of worldwide efforts to decrease their usage. Using natural ingredients like starch and glycerol, water, and vinegar (acetic acid) to make a flexible, biodegradable substance that resembles plastic is one of the most popular processes for making bioplastics.

Glycerol, vinegar, and water are combined with starch, and the mixture is heated until it thickens into a paste-like consistency. After spreading out and drying, this mixture forms a flexible, biodegradable substance that resembles plastic.

Role of Each Component:

1. Starch:

It serves as the bioplastic's primary structural component. Its hydrogen bonds break when heated with water, creating a flexible thermoplastic substance (Mali et al., 2008).

2. Glycerol:

It acts as a plasticizer to make the finished product more flexible. The bioplastic gets softer and more flexible as the glycerol concentration rises (Abdel Hamid et al., 2025).

3. Water:

It helps in dispersing glycerol uniformly and dissolving starch, it is necessary for the

gelatinization of starch (Rahmatiah Al Faruqy & Liew, 2016).

4. Vinegar (Acetic Acid):

It adjusts the mixture's pH and helps in the breakdown of starch chains, enhancing the bioplastic's texture and qualities (Abdel Hamid et al., 2025).

Simplified Process Equation:

Starch + Glycerol + Water + Heat + Acetic Acid → Thermoplastic Bioplastic

Note: This is not a traditional chemical reaction but a simplified representation of the physical transformation during the heating process.

6. Conclusion

In this research, we made a comprehensive overview of food packaging, Bioplastic and its classification, and the application of starch and its modification methods. We describe here the production of bioplastic derived from natural sources for use in food packaging. This research targets to develop bioplastic films from corn starch. Starch-based bioplastic was synthesized by physical transformation of starch using glycerol as natural plasticizer, in the presence of acetic acid which helps in the breakdown of starch chains.

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