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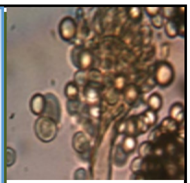

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Enhancing Sustainability: Optimisation of Eco-Friendly Corn Starch Based Bioplastic

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ABSTRACT

Plastic is ubiquitous worldwide, and the development of bioplastics necessitates the use of biodegradable and renewable resources. This study focuses on creating and characterizing biodegradable films using varying concentrations of corn starch. The bioplastic films are plasticized with glycerol and citric acid, the latter serving as co-plasticizers in different proportions. Starch concentrations range from 5% to 20% w/v, glycerol concentrations from 5% to 25% v/v, and citric acid content from 1% to 5% w/v. The resulting bioplastics are applied to butter paper to analyse surface morphology, solubility, and water retention. The films blended with glycerol as a plasticizer consistently showed promising results. Introducing citric acid as a co-plasticizer led to a bioplastic film with reduced water retention properties. This study outlines a simple, novel, and cost-effective technique to produce bio-based plastic.

INTRODUCTION

Environmental pollution is one of the most significant and widespread issues confronting humanity and other life forms on our planet today, affecting both industrialized and developing nations. The plastic we see consists of three-dimensional crosslinked networks, sometimes referred to as thermoset polymers. These are non-biodegradable and highly hazardous, as they emit a variety of lung irritants when burned [1]. However, excessive usage of plastics can have negative consequences, and the decomposition of these plastics takes more than 500 years, releasing harmful substances into the environment. It also affects humans by destroying the thyroid hormone axis or hormone levels. When these synthetic materials are disposed of in the environment, natural microbes cannot decompose them. As a result, these non-biodegradable plastics persist in the environment for an extended period, increasing the amount of solid waste produced. However, the Indian government, as well as the governments of other developed countries, are now increasingly worried about the disposal of these plastics.

It remains a significant issue, and their consumption has a serious impact on the ecosystem, vegetation, and animals [2]. Potential green solutions are urgently needed because of the environmental damage caused by plastics. As a result, biodegradable plastic emerges as a promising solution to this problem. Bioplastics have piqued people's curiosity since Henry Ford used corn and soybean oils to make his automobile parts in the early twentieth century. The bioplastic business offers promising prospects, as plastic is in enormous demand worldwide in this new era. Bioplastics are plastics made from renewable biomass sources such as vegetable fats and oils, maize starch, straw, wood chips, food waste, agricultural by-products, microorganisms, and used plastic bottles and other containers. Bioplastic is transparent, flexible, long-lasting, effective as a barrier, and heat-resistant. Bioplastics are categorized into three main types: starch-based, cellulose-based, and protein-based. Disposable items, such as packaging, crockery, cutlery, pots, bowls, and straws, are made from bioplastics [3].

One of the most essential sources in the formation of bioplastics is starch. Starch, as a natural biopolymer, has been utilized in several earlier research studies. Starch is the most abundant polysaccharide found in plants. Starch is a significant component of various plants, such as corn and wheat, containing 82% and 8% starch, respectively [4]. Starch is also abundant in rice. Starch is regarded as one of the most effective natural polymers due to its abundance, sustainability, affordability, and biodegradability. However, starch biopolymers are dissolvable in water and have low mechanical strength, which has proved to be a significant negative aspect [28]. Starch is a carbohydrate with the chemical formula $(C_6H_{10}O_5)$ n. Pure starch is a tasteless and odorless white-colored powder that is insoluble in cold water and has low mechanical strength, which has been demonstrated to be a significant negative aspect. It is composed of two polysaccharides: (i) amylose, which is a linear polymer, and (ii) amylopectin, which is a highly branched polymer [29]. The amylose content in starch is a crucial characteristic for bioplastics production, as it is responsible for gelatinization, which is necessary during film formation. The attributes of starch-based bioplastics strongly depend on the starch microstructure, particularly the amylose/amylopectin ratio.

About half of the bioplastics utilized in commercial settings are derived from starch. The process for creating starch-based bioplastics is straightforward and commonly employed for packaging purposes. However, because of the solid intermolecular and intramolecular hydrogen bonds in starch, native starch is not a true thermoplastic. A disadvantage of starch-based plastics is their brittleness. Therefore, it is a common practice to incorporate plasticizers during the production process. It ensures the plastic produced will be smooth, strong, flexible, and sturdy [30]. When added to a plasticizer, starch becomes more flexible and can be mixed with various polymeric materials for multiple applications [5]. Glycerol is incorporated into the starch as a plasticizing agent, and the desired properties of the bioplastics are attained by adjusting the amounts of the additives.

Glycerol is a simple polyol with the chemical formula $C_3H_8O_3$. Its IUPAC ID is propane-1,2,3-triol. It is a commonly available, inexpensive, environmentally friendly, non-toxic, colorless, and odourless, viscous liquid [6]. Citric acid (CA) is a trifunctional carboxylic acid that produces crosslinked starch. Adding citric acid can improve the polysaccharide's thermal tolerance and water stability. It has also been reported that citric acid positively affects the plasticization and melt-processing properties of starch [7]. During processing, glycerol and citric acid molecules enter the starch particles, replacing the starch's intermolecular and intramolecular hydrogen bonds, thereby destroying its crystallinity. The present research work aims to provide a promising bioplastic that causes minimal harm to the environment, exhibits good elasticity, and has a likely low production cost, making it an alternative to conventional and banned plastics that meet the changing requirements of modern society.

This study examines the synergistic effects of these three components by varying the concentrations of starch, glycerol, and citric acid to optimize bioplastic properties, an area that remains underexplored in the existing literature. Furthermore, this study employs sun drying for 5–7 days, unlike conventional oven or vacuum drying methods, which can lead to thermal degradation or uneven shrinkage [30]. Sun drying allowed for gradual moisture removal, reducing warping and enhancing film uniformity, which supports environmentally conscious production and offers practical advantages for low-resource applications. The degradation of this plastic was tested to assess its environmental friendliness, and it can be safely stated that it does not leave traces behind after a reasonable amount of time.

MATERIALS AND METHODS

Materials

Commercial corn starch (Blue Bird) and synthetic vinegar (Mausam) were purchased from the local grocery shop in Ahmedabad, Gujarat. Analytical grade glycerol - 99.5% v/v (SDFCL) and citirc acid-anhydrous (SDFCL) were used. Three different food coloring agents (blue, orange, and pink) were used to give color to the biofilm produced.

Preparation of Bio-plastic Film

Bioplastic film was prepared according to the following procedure: starch (the main biopolymer), in varying ratios, 10 mL of vinegar, 10 mL of glycerol (plasticizer) in varying ratios, and 10 mL of citric acid (co-plasticizer) in varying ratios were added to 100 mL of distilled water in a Volumetric Flask. The mixture was then poured into a 250 mL beaker from the flask and manually stirred with a glass rod for 5 minutes. A food coloring agent was then added to give the respective mixture color. Then, the mixture was heated on a burner for 5-7 minutes until it became slightly viscous and bubbles were visible, while being thoroughly stirred. Then, the cooked mixture was spread uniformly onto butter paper and allowed to sun-dry. It took approximately 5-6 days for the mixture to dry, after which the spread film was carefully removed with a spatula or by hand. Similarly, fifteen samples were prepared for different compositions of starch and plasticizer (**Fig. 1**).

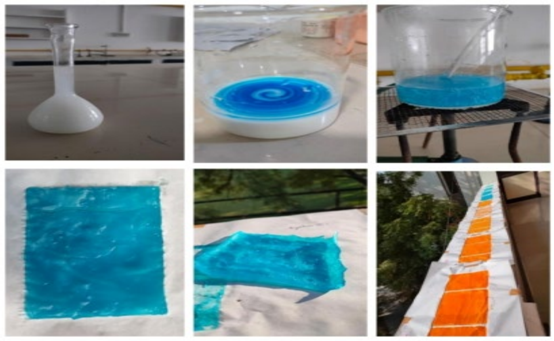

Fig. 1. Preparation of bioplastic film.

Bioplastic Analysis for Physical Properties

Bioplastic film's physical (opacity, viscosity, thickness, texture) and mechanical parameters (flexibility and stiffness) were visually observed, and respective conclusions were made [14,15,18,20].

Characterization

Water Absorption

Water absorption by bioplastics was found from the slightly modified ASTM D5229 standards [31]. Bioplastic samples with a size of 3*3 cm² were first dried in an oven at 85 °C for 30 min to allow for measuring their dry weight (Wi), followed by placing them in a 50 ml Petri dish filled with distilled water at room temperature for 3 h. After three hours, the bioplastic was obtained by filtering the water, and its weight was then measured to determine its final weight (W_f). The absorption of water was found using the following formula [8].

$$\text{Water Absorption (\%)} = \frac{wf - wi}{wi} \times 100$$

where, W_i = initial mass (g); W_f = final mass (g).

Water Solubility

Bioplastic samples of size 3 × 3 cm² were first dried in an oven at 85 °C for 20 min to allow for measuring their dry weight (Wi), followed by placing them in a 70 ml beaker of distilled water at room temperature (25 °C) and 175 rpm in a rotary shaker for 24 h. After 24 hours, the bioplastic residue was obtained by filtering the water, drying it in an oven at 85 °C for 20 minutes, and then weighing it to find the final weight (W_f) [9]. The solubility was found using the following formula.

$$\text{Water Solubility (\%)} = \frac{wf - wi}{wi} \times 100,$$

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where W_i = initial mass (g); Wf = final mass (g).

Solubility Test

The biofilm prepared was studied for its solubility. The solubility test was conducted to assess the persistence of these bioplastic materials, following the procedure outlined in [10]. The sample was cut into small pieces and inserted into different test tubes containing solvents such as ammonia, acetic acid, acetone, sulphuric acid, and dichloromethane. The solvents were chosen to determine the activity of the material, considering parameters such as a highly acidic solvent, a polar solvent, and a weak acid.

Fourier Transformation Infrared (FTIR) Spectroscopy

FTIR spectra of a starch biofilm (Starch 10%, Citric acid 3%, and Glycerol 10%) were performed using FTIR (Frontier Perin Elmer FTIR Spectrophotometer). FTIR spectrum was studied in the range of 4000–400 cm^{-1} [11].

Degradation

The biodegradation of the final developed plastic, which had an optimum value of starch, glycerol, and citric acid, was carried out according to the soil burial method, following the ASTM D5338-15 protocols [32]. Two 250 ml beakers were used for the test. The bioplastic film was cut into 2 cm x 2 cm dimensions, and each glass beaker was filled with approximately 150 g of mud. Pre-weighed films were noted for their initial weight before exposure to soiling conditions and then placed in beakers at a depth of 5 cm from the mud surface [12]. One of the film samples was sprinkled with water to study the effect of moisture content on the sample's degradation, while the other was without moisture. These two samples were observed for one month. The degradation rate was evaluated based on the data obtained by plotting a graph.

RESULTS AND DISCUSSIONS

Physical Properties

Thickness

The thickness of the film increased with increasing starch concentration from 5% to 20% (w/v). An increase in starch concentration correlates with elevated levels of amylose and amylopectin, leading to a greater solids content in the film-forming solution. Consequently, this results in the formation of a more viscous paste, which gives rise to thicker films [13]. Additionally, the thickness increases with the addition of plasticizer, as the plasticizer influences the intermolecular chain network rearrangement and organization, resulting in an increase in the biodegradable thickness of the plastic [14,29].

Hydrophilic Nature

The high hydrophilicity of the starch is attributed to this result, which is due to an increase in amylose concentration with an increase in starch content and glycerol. So, these bioplastics have a high number of hydroxyl groups. Due to the significant difference in electronegativities between hydrogen and oxygen, the –OH group becomes highly polar [15]. This polarity gives the biofilm a strongly hydrophilic nature. Additionally, as the glycerol plasticizer content increases, the bioplastic's water content also increases, and the biofilm's hydrophilic property improves [30].

Texture

The bioplastics produced had different surfaces on each side [15]. The surface in contact with the butter-paper is rough and opaque, while the interface exposed to the air is glossy and smooth. Some intact starch granules are visible in a 10% starch concentration. The biofilm (**Fig. 2**) indicates that the starch was not fully gelatinized during the film-forming process. Non-gelatinized starch granules are also present in biofilms with 9% and 10% starch concentration. Starch dissolution is understood to be incomplete since amylopectin-rich fractions may remain insoluble and undamaged [16], as evidenced by a 10% starch concentration. Biofilm has a high amylopectin fraction; this molecule can be responsible for insoluble material points in the film. A similar result was found for an aqueous corn starch dispersion (10% w/w), with glycerol added as a plasticizer (15%, 20%, and 25% v/v), as seen in **Figs. 2, 3 & 4(c)**.

It has been observed that the maximum number of non-gelatinized starch granules is found in biofilms with 20% and 25% (v/v) glycerol concentration. However, the 5% and 10% biofilms have very smooth and delicate textures, with some areas exhibiting a 15% concentration. Biofilm contains non-gelatinized starch granules, and some of these granules have a smooth surface. It is reported that the swelling and gelatinization of starch is retarded by the presence of glycerol.

The films are homogeneous, without pores or cracks, and the starch molecules are well dispersed, without non-gelatinized granules, unlike those observed in films made from crosslinked starch [30]. Starch mixed with citric acid concentration ranging from 1% to 5% (w/v) (**Fig. 5**). In the biofilm with increased conc. No residual granular structures are left of citric acid, and the surface is smoother than that of an increased %(v/v) concentration of glycerol. The acidity of citric acid promotes the fragmentation and dissolution of cornstarch granules [17].

Fig. 2. Biofilm made of 10% (w/v) starch with 15% (v/v) glycerol as plasticizer with 1% (w/v) citric-acid as co-plasticizer.

Fig. 3 Biofilm made of 10% (w/v) starch with 20% (v/v) glycerol as plasticizer with 1% (w/v) citric acid as co-plasticizer.

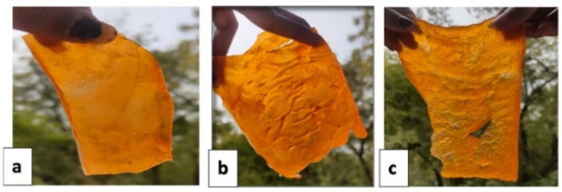

Fig. 4. (a) Biofilm with 5% (v/v) glycerol (brittle & inflexible), (b) Biofilm with 10% (v/v) glycerol (optimal concentration), (c) Biofilm with 25% (v/v) glycerol (moist & sticky).

Fig. 5. (a) Biofilm with 2% (v/v) citric acid (flexible), (b) Biofilm with 3% (v/v) citric acid (optimal concentration), (c) Biofilm with 4% (v/v) citric acid (moist & sticky), (d) Biofilm with 5% (v/v) Citric acid (moist & sticky).

Opacity

The opacity was verified by an increase in their opacity with increased starch concentration from 5% to 20% (w/v). This property depends on starch origin (amylose/amylopectin ratio, size, and shape of starch granules) and thickness. Matrices that contain more amyloses are thicker and, thus, more opaque [18]. In the current research, this finding is linked to the rise in amylose content, which has a direct relationship with the concentration of starch in the film. According to a previous study [13], film opacity is critical if the film is used as a food surface coating. Transparent films are characterized by low opacity. Biofilms with 15% and 20% glycerol (Figs. 2 and 3) exhibited large craters, which are likely due to air bubbles. This shows the uneven distribution of glycerol on the surface of the plastic film. Bubbles were spread very much on the surface of the film. The bubble caused the surface of the film to be mildly smooth [19].

Viscosity

It has been observed that the viscosity of the paste increases as the concentration of starch increases. A 15% and 20% starch concentration yield a highly viscous paste, whereas a 10% starch concentration results in a less viscous paste that is very slippery. This is because amylopectin is a more remarkable molecule than amylose. Starch becomes soluble in water when heated, causing the grains to swell and burst. Due to this, the semi-crystalline arrangement is also lost, and the minor amylose particles begin percolating out of the granule [20], forming a network. This network compresses water and increases the mixture's viscosity. This procedure is known as starch gelatinization, and amylose is imperative in the initial stages of cornstarch gelatinization [21]. While heating, the starch becomes a paste, and the viscosity increases. High-amylose starch is an innovative reserve for use as a filler in packing materials.

Table 1. Surface morphology of varied starch, glycerol, and citric acid biofilm combinations.

Sr. No	Combinations	Surface Morphology				
		Texture	Cracking	Flexibility	Opacity	Viscosity
1	5 % Starch + 10 % Glycerol + 1 % CA	+++	Wet & Slimy	Wet & Slimy	Wet & Slimy	-
2	6 % Starch + 10 % Glycerol + 1 % CA	+++	-	-	+	+
3	7 % Starch + 10 % Glycerol + 1 % CA	+++	-	+	++	+
4	8 % Starch + 10 % Glycerol + 1 % CA	+++	-	++	++	++
5	9 % Starch + 10 % Glycerol + 1 % CA	+++	-	++	++	++
6	10 % Starch + 10 % Glycerol + 1 % CA	++	+	+++	+++	+++
7	15 % Starch + 10 % Glycerol + 1 % CA	-	++	-	+++	+++
8	20 % Starch + 10 % Glycerol + 1 % CA	-	+++	-	+++	+++
9	10% Starch + 5 % Glycerol + 1 % CA	+++	++	++	+	+
10	10 % Starch + 15 % Glycerol + 1 % CA	++	-	+++	++	++
11	10 % Starch + 20 % Glycerol + 1 % CA	+	-	+	++	+++
12	10 % Starch + 25 % Glycerol + 1 % CA	+	++	+	+++	+++
13	10 % Starch + 10 % Glycerol + 2 % CA	++	-	++	+	++
14	10 % Starch + 10 % Glycerol + 3 % CA	++	-	++	+	++
15	10 % Starch + 10 % Glycerol + 4 % CA	+++	-	+	++	++
16	10 % Starch + 10 % Glycerol + 5 % CA	+++	+	+	++	++

Note:
Texture: Rough (-), Slightly Smooth (+), Moderately Smooth (++), Highly Smooth (+++)
Cracking: No Cracking (-), Slight Cracked (+) , Moderate Cracked (++) , Highly Cracked (+++)
Flexibility: Not Flexible (-) , Slightly Flexible (+) , Moderately Flexible (++) , Highly Flexible (+++)
Opacity: Translucent (+) , Slightly Opaque (++) , Moderately Opaque (+++)
Viscosity: Slightly viscous (+) , Moderately Viscous (++) , Highly Viscous (+++)

Mechanical Properties

Flexibility

To determine the flexibility of plasticized bioplastics with glycerol, the influence of starch and glycerol was evaluated using regression analysis, as both starch and glycerol contributed to the flexibility of the bioplastics. The flexibility increased with increasing starch concentration, but this increase was observed up to 9% and 10% (w/v) of starch. In comparison, there was a decrease in this property for the bioplastic containing a concentration of 15% (w/v) of starch. On the effect of glycerol, this study found that the lower the concentration, the greater the flexibility of the bioplastics [30].

The starch networks combine with glycerol molecules as glycerol is added, reducing starch-starch interactions. As glycerol is added, it disrupts the starch chains, causing a reduction in rigidity and increased chain mobility [22]. It was found that the optimum value of glycerol plasticizer is 10% (v/v), as bioplastics produced with 5% (v/v) were brittle and inflexible, while those produced with 15%, 20%, and 25% were moist and sticky. It is seen that with an increasing amount of plasticizer, the flexibility and stickiness of the bioplastic also increase. Due to the smaller molecular size of the plasticizer, it is sufficient to reduce internal hydrogen bonds, thereby increasing intermolecular distances. The changes in the starch microstructure facilitated the entry of plasticizer into the starch matrix. Plasticizers that have entered the starch molecule further reduce the interaction between starch molecules (cohesion) by forming hydrogen bonds between hydroxyl groups in starch molecules and plasticizer molecules, thereby increasing the bioplastic's flexibility [23]. The effect of plasticizer concentration (10% - 25%) on the flexibility of the biofilm has an inverse behavior compared with its corresponding tensile strength.

Stiffness

The film stiffness was influenced by the concentrations of starch and glycerol, as well as their interaction. The higher the starch

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concentration, as seen in the biofilms with 20% and 25% starch content, the greater the stiffness of the film. Conversely, the lower the plasticizer concentration, as seen in the 5% glycerol content, the higher the material's stiffness.

Water Absorption

Water uptake is often referred to as water absorption, where bioplastics are expected to have low water absorption. Water absorption values were noted to increase with the increase in starch concentration. Starch is hydrophilic, and the hydroxyl groups in starch are attracted to water. Added to this is the fact that the gelatinisation process also ruptures starch granules, allowing water to diffuse quickly into them [24].

Biofilm with a starch concentration of 9% showed a percentage of water uptake of 89.65%, and 10% showed a water uptake of 78.77%. In comparison, biofilms with lower starch concentrations showed a lower percentage of water uptake and varied little, ranging from 6% to 8%. The films were determined to have a water uptake percentage of more than 50% because biopolymers are hydrophilic (**Fig. 6**). In addition to the water molecules interacting with the hydroxyl groups in the starch structure, the plasticization of biopolymers with glycerol is also an essential factor in this study.

Water uptake value increases as glycerol plasticizer is increased from 5% to 25% (v/v), where 20% shows a maximum value of water uptake of 79.61%, where 5% shows a lower percentage of water uptake of 61.26% (**Fig. 7**). As glycerol is a hydrophilic low molecular carbohydrate, it tends to absorb water depending on the number of hydroxyl groups present and the molecular weight of its structure. Glycerol has three carbons attached to its backbone, with one hydroxyl group attached to each carbon, which causes the molecules to bind to the highest amount of water corresponding to the weight portion. It can be concluded that the addition of glycerol plasticizers has increased the hydrophilic properties of the biofilm.

As reported in earlier research [17], the addition of citric acid improved the water resistance of biofilm; however, the equilibrium water content varied little when citric acid concentration increased from 1% to 5% (w/v) (**Fig. 8**). Citric acid can decrease the shear viscosity and improve the fluidity of the film.

Fig. 6. Water Absorption test of different starch-concentrations (w/v) %.

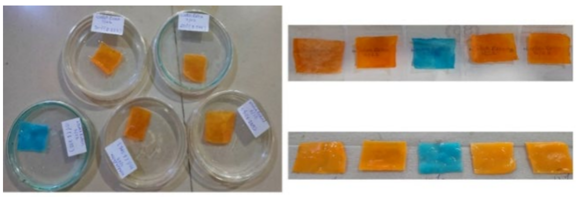

Fig. 7. Water Absorption test of different glycerol concentrations (v/v) %.

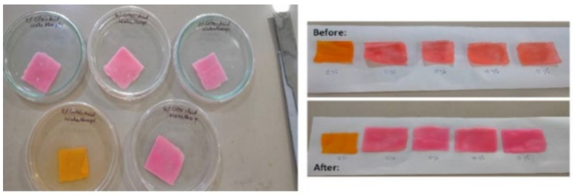

Fig. 8. Water Absorption test of different citric acid concentrations (v/v) %.

Water Solubility

The results for the solubility of bioplastics ranged from 34.17% to 55.10%, and for starch concentration, they ranged from 6% to 10% (w/v). There was an increase in solubility with increasing starch concentration. The higher concentrations of starch can explain this result compared to the plasticizer used in the production of bioplastics. The glycerol molecule contains merely three unbound hydroxyl groups, whereas the starch molecule possesses numerous; therefore, certain hydroxyl groups in starch remain open for interaction with water, making the bioplastic more soluble [15].

The water solubility of bioplastic increased with the addition of plasticizer. Among the plasticized samples, the glycerol-plasticized samples had the highest water solubility. The results are consistent with the previous findings [9], plasticizers are hydrophilic (especially, polyols) and play a substantial role in causing the interactions between polymer molecule chains to become weaker, increasing the free space between chains. This helps water diffuse into the polymer matrix, thereby enhancing the solubility of the plasticized bioplastic films (Figs. **9**-**13**).

The solubility of films in water as a function of citirc acid content is presented in **Fig. 11**. It is seen that the biofilm maintained its integrity, i.e., it did not dissolve or break apart during the solubility test, which indirectly confirms the crosslinking [25]**.** The systems containing lower CA amounts, i.e., up to 3% (w/v), exhibited similar solubility, around 28% in water. However, when CA content was increased, the solubility increased to 35.71%.

According to a previous study [26], there is the possibility of cornstarch acidolysis (It has been reported that at very low pH, the reduction of starch chains could occur), which could subsequently lead to increased solubility in water (**Fig. 10**). The increment of water solubility is ascribed to the plasticizer's effects. Due to their hydrophilic nature, plasticizers minimize the interactions between bio-composite particles, promoting solubility and increasing the polymer particles' propensity to bind water [27]**.**

Fig. 9. Water Solubility test of different starch (w/v) % and glycerol concentrations (v/v) %.

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Fig. 10. Water Solubility test of different citirc acid concentrations (v/v) %.

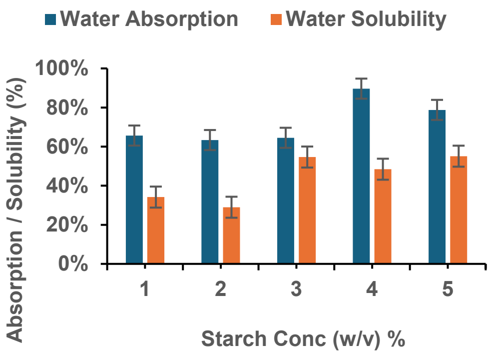

Fig. 11. Water-Absorption and Water Solubility (%) in varied starch concentration.

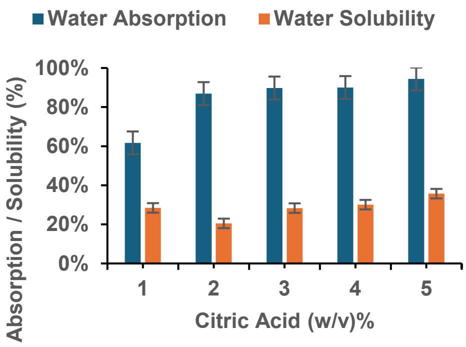

Fig. 12. Water-Absorption and Water Solubility (%) in varied citric acid concentration.

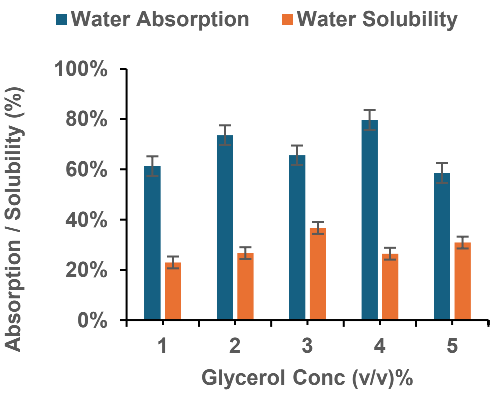

Fig. 13. Water-Absorption and Water Solubility (%) in varied glycerol concentration.

Solubility in Solvents

The results of the solubility test of biofilm in different solvents are shown in **Table 2**. The study results revealed that the material was initially insoluble in water, making it a more suitable candidate for bioplastic material, but it became soluble over time. It was also insoluble in acetone (polar solvent), acetic acid (polar solvent/weak-acid), ammonia (polar solvent), partially soluble in DCM (polar solvent), and utterly soluble in sulphuric acid (strongly acidic solvent) (**Fig. 14**). Starch molecules degrade via hydrolysis, lowering their molecular size and enhancing their solubility. This is an exothermic reaction that releases heat and steam. Solubility plays a significant role in selecting a sustainable biomaterial for bioplastics because it cannot be considered a bioplastic if it is soluble in water and other solvents. Results from the solubility test showed that the material is insoluble in water and other organic solvents, making it more efficient in producing bioplastics at a low cost.

Table 2. Solubility Test in Different Solvents.

Sr. No	Solvents Used	Insoluble	Partially Soluble	Soluble
1	Acetone	+	-	-
2	Ammonia	+	-	-
3	Sulphuric Acid	-	-	+
4	Acetic Acid	+	-	-
5	Dichloro-Methane	+	-	-

Abbreviations: (+): Positive; (-): Negative

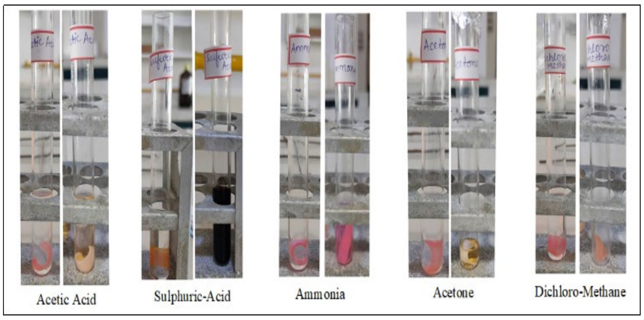

Fig. 14. Solubility in different solvents.

FTIR Analysis

The use of glycerol as a plasticizer in starch increases hydrogen bonding, a stretching vibration seen around 3300 cm^{-1}, reducing intermolecular forces and enhancing flexibility. Citric acid leads to esterification or crosslinking with starch, resulting in a new band at around 1700 cm^{-1}, which improves mechanical properties and thermal stability. When combined, glycerol and citric acid synergistically enhance material properties and reduce the crystalline structure of starch, thereby increasing amorphousness. These modifications make starch-based bioplastics more suitable for applications like biodegradable packaging, with improved flexibility, strength, and biodegradability, as confirmed by FTIR analysis (**Fig. 15**) [30].

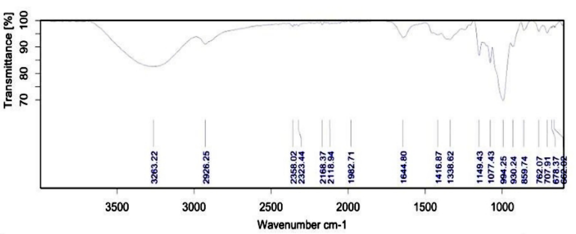

Fig. 15. Fourier transformation infrared (FTIR) spectroscopy.

Degradation

This aims to determine how long bioplastics take to biodegrade in the environment. The biodegradability of a bioplastic depends on its physical and chemical properties, such as its surface area, hydrophilicity or hydrophobicity, chemical structure, and molecular weight. As the previous study stated [28], the percentage weight loss during soil burial biodegradation (Fig. 16) is caused by microorganisms invading the substrate and absorbing water—the act of microorganisms feeding upon the substrate contributes to the percentage weight loss. As reported in earlier research [19], the addition of plasticizer increases the biodegradability of the samples, which can be attributed to the greater water uptake and solubility of the samples, resulting from the hydrophilicity of plasticizers.

Glycerol's higher water absorption capacity enables the biodegradable plastic to absorb moisture quickly [14], which weakens its structure, promotes the growth of microbes, and accelerates the breakdown of the starch polymer chains. This combination results in a faster degradation rate, a crucial characteristic for the environmental benefits of starch-based bioplastics, particularly in disposal or composting environments. While in dry conditions, starch-based bioplastics tend to degrade more slowly because there is less water available to interact with the material [30] (**Fig. 16**).

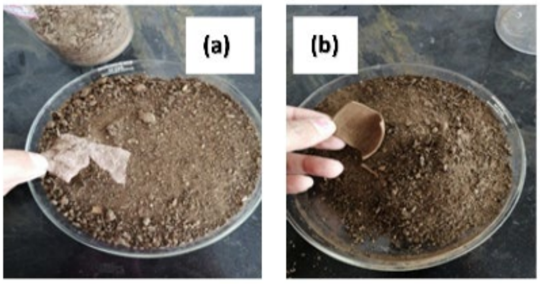

Fig. 16. Degradation: (a) With moisture (b) Without moisture.

The degradation rate occurred slowly for the first three days, as shown in Table 3, because the soil microbial biota acclimated to the new environment and increased after four days. Soil microorganisms produce extracellular hydrolytic enzymes. A significant reduction in the sample weight was realized by the 14th day, consistent with the expected results observed upon completion of 31 days of incubation. Accordingly, the degradation percentage was approximately 66.63% in the case of a sample with a high moisture content; meanwhile, 19.56% of biodegradation was observed within the soil under natural conditions. Hence, the results showed that biodegradation occurs faster in the presence of extra moisture content than in natural conditions (**Fig. 17**). Based on these results, we can conclude that the bioplastic produced using corn starch degrades within nearly two to three months for sample B and perhaps four months or more for sample A.

Table 3. Biodegradation (%) of bioplastic film.

Day	Sample Weight(g) without moisture Sample (A)	(%) Weight Loss with respect to initial weight	Sample Weight (g) without moisture Sample (B)	(%) Weight Loss with respect to initial weight
1	2.254	0.0	2.994	0.0
3	2.224	1.33	2.932	2.07
8	2.197	2.52	2.515	15.99
14	1.945	13.70	2.190	26.85
21	1.880	16.59	1.152	61.52
28	1.813	19.56	0.999	66.63

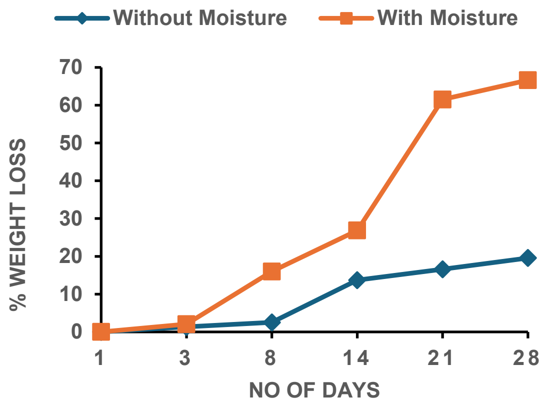

Fig. 17. Comparative (%) degradation of bioplastic film with & without moisture.

CONCLUSION

The study attempted to pique interest in sustainable and experimental biobased materials. Therefore, vinegar, starch, glycerol, citric acid, and water were used to create a starch-based bioplastic material that might be used as an emerging novel material. The use of maize starches as a source and various types of plasticizers can have a considerable impact on the physical and chemical properties of created bioplastics, such as water absorption, water solubility, biodegradability, flexibility, and stiffness, according to the findings of this study. Adding citric acid extends the material's shelf life and improves its mechanical qualities. In water, the average water solubility is 28.31%. The sample's biodegradability is reached in less than a month. The research has shown that starch-based bioplastics stand out over other source-based bioplastics due to their cost-effectiveness, abundance, biodegradability, and renewable nature. They contribute to reducing the environmental impact of plastic waste and offer a sustainable alternative to traditional petroleum-based plastics. However, the degradation rate and performance of starch-based bioplastics can vary depending on factors like moisture, temperature, and modifications made during production. The findings provide an eco-friendly basis for industrial applications, particularly in the production of packaging and disposable goods, where biodegradability, strength, and flexibility are essential. By optimizing these components, industries can tailor bioplastic formulations to meet their specific performance requirements without relying on petroleum-based inputs. This study's use of sun drying makes the procedure more affordable and energy-efficient than traditional drying techniques, which makes it more accessible to rural populations and small-scale businesses. Additionally, it reduces heat deterioration, producing more stable and consistent films. Bioplastic manufacturing mainly focuses on sustainability issues, designing and perceiving the unpredictable, and searching for "new" materials for a greener and more sustainable future. As a result, the demand for bioplastics and their production should be boosted to ensure a bright and sustainable future. The hybridization of proposed starch materials with other biomaterials and plasticizers, along with more advanced and energy-efficient drying techniques, would be a fascinating area of investigation for this study.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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