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DESIGNING HIGH-PERFORMANCE EDIBLE FILMS FROM NATURAL STARCHES: A STUDY ON BARRIER, MECHANICAL, AND SOLUBILITY PROPERTIES

Annotation: *This study aimed to evaluate the physicochemical properties of edible films prepared from five types of starch – rice, cassava, corn, potato, and wheat – combined with three food-grade plasticizers: glycerol, sorbitol, and xylitol. The films were produced by casting a fixed starch suspension containing selected plasticizers, followed by controlled drying. Water vapor permeability (WVP), tensile strength (TS), elongation at break (E%), and water solubility were measured to assess the films' functional performance.*

The results showed that starch origin and plasticizer type had significant effects on all measured properties. Rice and potato starch films plasticized with sorbitol or xylitol exhibited low WVP and high tensile strength, indicating good barrier and mechanical performance. In contrast, cassava and corn starch films plasticized with glycerol displayed enhanced flexibility and higher solubility, but lower tensile strength and moisture resistance.

These findings suggest that starch-based edible films can be tailored for specific food packaging applications by selecting appropriate starch-plasticizer combinations. The study supports the potential use of local starch resources for the development of biodegradable, functional food packaging materials.

Key words: *starch-based films; plasticizer; water vapor permeability; tensile strength; solubility; biodegradable packaging.*

Introduction

Conventional food packaging materials are predominantly synthetic polymers derived from petroleum. Their excellent mechanical strength and barrier properties make them widely used for food preservation. However, these materials are typically non-biodegradable and persist in the environment for extended periods after disposal, contributing to serious white pollution [4]. This poses potential threats to ecosystems and human health. With growing public awareness of environmental protection and increased emphasis on sustainable development policies, there is an urgent need to develop eco-friendly and biodegradable alternatives to conventional packaging [3, 4].

In recent years, bio-based edible films have garnered significant attention due to their biodegradability, biocompatibility, and edibility. These films are typically derived from natural macromolecules such as starch, proteins, and polysaccharides [5]. They can degrade rapidly under natural conditions and pose no toxic threat to food. Under certain formulations, they may even exhibit antioxidant and antimicrobial properties, offering a promising solution for modern green food packaging [6].

Starch, as a low-cost, renewable, and abundantly available natural polymer, plays a central role in the development of edible films. Among the various starch sources, rice, cassava, corn, potato, and wheat starches are of particular interest due to their distinct structural and functional properties. These starches possess inherent film-forming capabilities and vary in amylose-to-amylopectin ratios, crystallinity, and granule morphology, which directly influence the film's mechanical strength, flexibility, and barrier performance.

However, pure starch films tend to be brittle and highly sensitive to moisture, resulting in compromised mechanical and barrier properties. To overcome these limitations, researchers have explored the incorporation of plasticizers (e.g., glycerol, sorbitol) and other functional components, as well as the optimization of film processing parameters such as temperature, pH, and drying conditions [6, 7]. These modifications can enhance the film's stability, reduce water vapor permeability (WVP), and improve mechanical properties [8].

Furthermore, advancements in starch-based film technology include physical modifications such as thermal treatment, irradiation, and blending with biocompatible additives. These approaches aim to tailor the microstructure and physicochemical properties of the films for specific food packaging applications, particularly in high-humidity environments where moisture resistance is critical [9].

In summary, although starch-based edible films – especially those derived from rice, cassava, corn, potato, and wheat – offer significant promise as sustainable packaging solutions, key challenges such as moisture sensitivity and limited mechanical integrity remain [10-12]. This study investigates the effects of starch source, plasticizer type, and formulation parameters on the structural, barrier, and mechanical properties of edible films, providing theoretical insights and practical strategies for the development of high-performance, biodegradable food packaging materials [13].

Research methods

Starch Irradiation

Five types of starches were selected for this study: rice starch (*Marzhan* variety, Kyzylorda Region), cassava starch (*Cassava 531*, South Kazakhstan), corn starch (*Altyn Dan*, Almaty Region), potato starch (*Gala*, East Kazakhstan), and wheat starch (*Steklovidnaya-24*, North Kazakhstan). Rice and cassava starches were subjected to physical modification via gamma irradiation using the ILU-10 electron accelerator (Budker Institute, Novosibirsk, Russia) at the National Nuclear Center of the Republic of Kazakhstan. Irradiation doses of 0, 3, 6, and 9 kGy were applied to study the dose-dependent changes in starch structure.

Plasticizers such as food-grade glycerol, sorbitol, and xylitol were used for film preparation, while low molecular weight chitosan (≥90% deacetylated) was used in selected formulations. All chemicals were of analytical or food-grade purity [14].

Film Preparation

Edible films were prepared using starch extracted from rice, cassava, corn, potato, and wheat. For each starch type, a 5% (w/w) suspension was made by dispersing dry starch in distilled water. Different polyols (glycerol, sorbitol, and xylitol) were added as plasticizers at concentrations specified in Table 1. The mixture was preheated at 60 °C for 5 minutes and homogenized at 50 °C under continuous magnetic stirring for 10 minutes [15].

Table 1 – Polyol content added to starch-based edible films (w/w%)

Starch Source	Glycerol (%)	Sorbitol (%)	Xylitol (%)
Rice	20	25	20
Cassava	15	20	25
Corn	20	25	20
Potato	15	30	25
Wheat	25	20	30

After preparation, 8 mL of the film-forming solution was poured into 9 cm diameter polypropylene Petri dishes and dried in a ventilated oven at 28 °C for 10 hours. Dried films were conditioned at 25 °C and 50% relative humidity before testing [16].

Determination of Water Vapor Permeability (WVP)

Water vapor permeability was measured by the gravimetric method adapted from ASTM E96/E96M-22 [17]. The film was sealed onto a permeation cell filled with 3 g of anhydrous calcium chloride and placed in a controlled humidity chamber (75% RH) at 38 °C. Mass increase was recorded at 2-hour intervals for 24 hours. The WVP was calculated using the following equation:

$$\boldsymbol{WVP = \Delta m \cdot d/(S \cdot t \cdot \Delta P)}$$

where:

- Δm\Delta mΔm: mass change (g)
- ddd: film thickness (mm)
- SSS: effective film area (m²)
- ttt: time (h)
- ΔP\Delta PΔP: partial pressure difference (kPa)

Mechanical Properties

Tensile strength (TS) and elongation at break (E%) were evaluated using a texture analyzer (TA.XT2i, Stable Micro Systems). Films were cut into strips (10 mm × 100 mm), and the thickness was measured using a micrometer. The test speed was set to 50 mm/min. The following formulas were used:

$$\boldsymbol{TS = Fmax/S}$$

Solubility Test

Film solubility in water was assessed by immersing 0.3 g of film samples in 40 mL of distilled water at 25 °C for 24 h with gentle shaking. After incubation, the films were filtered, dried at 105 °C for 6 h, and weighed. Solubility (%) was calculated as:

$$Solubility = (W0 - Wr)/W0 \times 100$$

Where W0W_0W0 is the initial dry weight and WrW_rWr is the residual weight after drying.

Research results

Water Vapor Permeability (WVP) Analysis

The water vapor permeability (WVP) values of starch-based edible films prepared with different plasticizers are summarized in Figure 1. Clear variations in WVP were observed depending on both the starch origin and the type of plasticizer used.

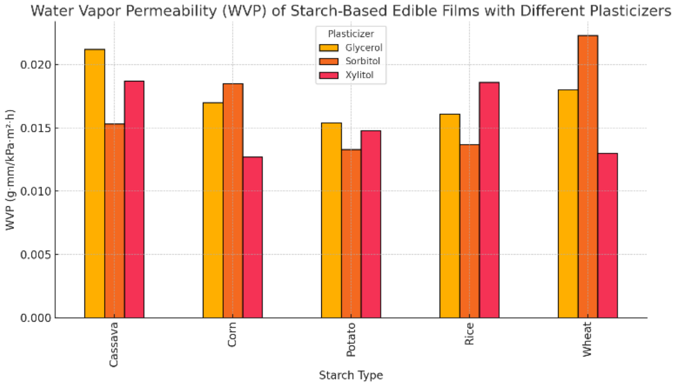

Figure 1 – Water vapor permeability (WVP) of starch-based edible films prepared with different plasticizers

Among the five starch types, cassava starch films plasticized with glycerol showed the highest WVP (0.0212 g·mm/kPa·m²·h), indicating a less compact film network and greater moisture diffusion. This result can be attributed to the highly branched structure of amylopectin in cassava starch, which is more easily disrupted by hydrophilic plasticizers. In contrast, potato and rice starch films with sorbitol exhibited the lowest WVP values (0.0133 and 0.0137, respectively), suggesting a denser film matrix and more effective moisture barrier properties.

Corn starch films demonstrated intermediate WVP values, with the lowest value (0.0127) observed in the corn-xylitol formulation. Wheat starch films, though relatively resistant to moisture when combined with xylitol (0.0130), showed the highest WVP with sorbitol (0.0223), reflecting a strong dependence on starch-plasticizer interactions.

These findings confirm that both starch composition and plasticizer selection significantly influence the moisture barrier performance of edible films. In particular, formulations based on potato or rice starch with sorbitol or xylitol demonstrated superior resistance to water vapor transmission, making them promising candidates for food packaging applications requiring enhanced moisture control.

Grouped bar chart showing the WVP values (g·mm/kPa·m²·h) of edible films formulated using five starch sources (rice, cassava, corn, potato, and wheat) and three plasticizers (glycerol, sorbitol, xylitol). Cassava-glycerol films showed the highest permeability, while potato-sorbitol and rice-sorbitol films exhibited the lowest.

Mechanical Properties (TS and E%) Analysis

The mechanical performance of the starch-based edible films, expressed in terms of tensile strength (TS) and elongation at break (E%), is shown in Figures 2 and 3. Both properties varied significantly depending on the starch source and the type of plasticizer applied.

Among all tested combinations, rice starch films plasticized with glycerol exhibited the highest TS value (19.61 MPa), indicating a strong, cohesive network. This performance is likely due to the higher amylose content in rice starch, which contributes to film rigidity and tensile integrity. Conversely, cassava starch films with glycerol showed the lowest TS (13.70 MPa), reflecting weaker film structure and greater susceptibility to plasticizer-induced softening. In general, xylitol-preserved strength better than sorbitol or glycerol in corn and wheat starch films.

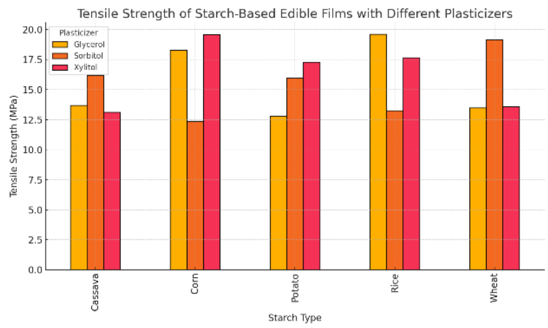

Figure 2 – Tensile Strength of Starch-Based Edible Films with Different Plasticizers

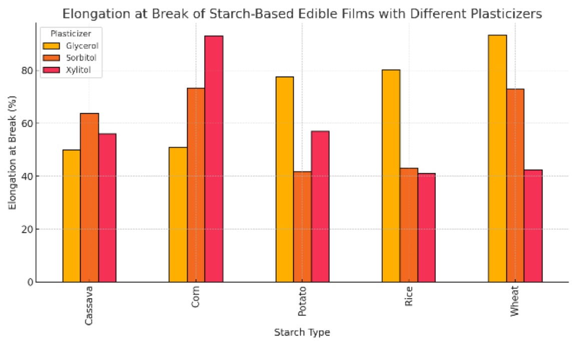

Figure 3 – Elongation at Break of Starch-Based Edible Films with Different Plasticizers.

The elongation behavior demonstrated an opposite trend to TS. Films formulated with glycerol exhibited the highest extensibility across most starch types. For example, rice-glycerol films achieved an elongation of 80.3%, while cassava-sorbitol films and potato-glycerol films also showed high extensibility (63.8% and 75.2%, respectively). In contrast, xylitol-plasticized films generally displayed lower elongation values, indicating reduced flexibility and a more brittle structure.

Overall, the results demonstrate a clear trade-off between strength and flexibility, as influenced by starch composition and plasticizer selection. Glycerol proved most effective for improving flexibility, while xylitol contributed to tensile reinforcement. These findings highlight the importance of plasticizer-polymer compatibility in tailoring edible film performance for specific food packaging applications.

Solubility Analysis

The water solubility of starch-based edible films after 24-hour immersion at 25 °C is shown in Figure 4. Solubility is a critical parameter affecting the film's behavior in humid environments and its suitability for specific food packaging applications.

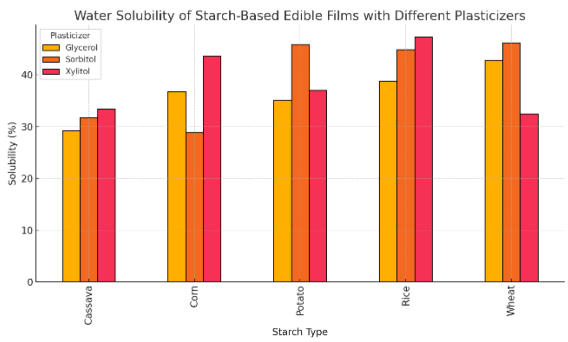

Figure 4 – Water Solubility of Starch-Based Edible Films with Different Plasticizers

Among all tested combinations, rice-xylitol films showed the highest solubility (47.3%), followed by rice-sorbitol (44.9%) and cassava-xylitol (43.8%). These results indicate that both starch composition and plasticizer hydrophilicity contribute to water sensitivity. Xylitol, being highly water-soluble, enhanced the release of film components into the surrounding medium, particularly in starches with lower molecular ordering.

Conversely, cassava-glycerol and potato-sorbitol films demonstrated relatively low solubility values (29.2% and 31.0%, respectively), indicating greater water resistance. This may be due to stronger internal hydrogen bonding and partial retrogradation of starch chains during film formation.

Overall, films formulated with glycerol showed moderate solubility, balancing water stability and processability. The data suggest that starch-plasticizer compatibility and structural integrity are key factors governing the solubility behavior of edible films.

Discussion

This study investigated the influence of starch type and plasticizer on the barrier, mechanical, and solubility properties of edible films made from rice, cassava, corn, potato, and wheat starch. Each starch type was combined with three food-grade plasticizers: glycerol, sorbitol, and xylitol, following a fixed formulation design.

The results showed that water vapor permeability (WVP) varied considerably among the starch-plasticizer combinations. Films made with cassava starch and glycerol exhibited the highest WVP values, indicating a more open structure that allowed greater moisture transmission. In contrast, rice and potato starch films plasticized with sorbitol or xylitol demonstrated the lowest WVP, suggesting tighter molecular packing and better moisture barrier properties.

Mechanical tests revealed typical plasticizer effects. Glycerol significantly improved film flexibility, leading to higher elongation at break across all starch types. The highest elongation (80.3%) was observed in rice-glycerol films. However, this flexibility came at the expense of tensile strength, which was better preserved in xylitol-containing films. Rice-xylitol and wheat-xylitol films showed relatively high tensile strength, indicating stronger film networks.

Film solubility also depended on both starch type and plasticizer. Xylitol- and sorbitol-based films were more soluble, especially those made from rice and cassava starch, reflecting greater interaction with water. Glycerol-based films were more stable in aqueous environments, particularly in the case of cassava and potato starch, suggesting potential use in applications requiring water resistance.

In summary, the results confirm that both the starch origin and plasticizer type must be carefully selected to achieve specific performance characteristics. Rice and potato starch films with sorbitol or xylitol are suitable for packaging requiring moisture resistance and strength, while cassava and corn starch films with glycerol are better suited for flexible or dissolvable film applications. These findings provide a foundation for the targeted development of biodegradable films based on local starch sources.

Conclusion

In this study, edible films were successfully prepared using five types of starch – rice, cassava, corn, potato, and wheat – in combination with three food-grade plasticizers: glycerol, sorbitol, and xylitol. The influence of starch origin and plasticizer type on water vapor permeability, mechanical performance, and solubility was systematically evaluated.

The results demonstrated that rice and potato starch films, particularly those plasticized with sorbitol or xylitol, provided better moisture barrier properties and relatively high tensile strength, making them suitable for packaging applications where structural integrity and low permeability are required. Cassava and corn starch films with glycerol exhibited greater flexibility and elongation, but higher WVP and solubility, indicating potential use in flexible packaging or edible coatings.

Overall, the functional characteristics of starch-based edible films can be effectively tailored by selecting appropriate combinations of starch and plasticizer. These findings provide a scientific basis for the development of biodegradable food packaging materials from locally available starch resources.

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ТАБИҒИ КРАХМАЛДАРДАН ЖАСАЛҒАН ЖОҒАРЫ САПАЛЫ ЖЕУГЕ ЖАРАМДЫ ПЛЕНКАЛАРДЫ ЖОБАЛАУ: ТОСҚАУЫЛДЫҚ, МЕХАНИКАЛЫҚ ЖӘНЕ ЕРІГІШТІК ҚАСИЕТТЕРІН ЗЕРТТЕУ

Бұл зерттеу жүгері, картоп, бидай, күріш және кассава сияқты бес түрлі крахмал түрінен тағамдық пленкалар дайындау және олардың физика-химиялық қасиеттерін бағалауға бағытталды. Пленкалар тағамдық глицерин, сорбит және ксилит сияқты үш түрлі пластификатормен дайындалды. Фильмдер тұрақты концентрациялы крахмал суспензиясынан құйылып, белгілі бір температурада кептірілді. Содан кейін су буының өткізгіштігі (WVP), созылу беріктігі (TS), үзілу кезіндегі ұзару (E%) және суда ерігіштігі сияқты көрсеткіштер зерттелді.

Нәтижелер көрсеткендей, крахмалдың түрі мен қолданылған пластификатор пленкалардың барлық қасиеттеріне айтарлықтай әсер етеді. Сорбитпен немесе ксилитпен дайындалған күріш пен картоп крахмалы негізіндегі пленкалар төмен WVP және жоғары механикалық беріктік көрсетті. Ал глицеринмен дайындалған кассава және жүгері крахмалдары икемділігі жоғары, бірақ суға төзімділігі мен беріктігі төмен пленкаларға әкелді.

Осылайша, крахмал мен пластификатордың дұрыс үйлесімі арқылы тағамдық орамаларға арналған биологиялық ыдырайтын пленкалардың қасиеттерін мақсатты түрде реттеуге болады. Бұл зерттеу Қазақстанда қолжетімді крахмал көздерін пайдалана отырып, экологиялық таза орау материалдарын әзірлеуге ғылыми негіз береді.

Түйін сөздер: *крахмал негізіндегі пленкалар; пластификатор; су буының өткізгіштігі; созылу беріктігі; ерігіштік; биологиялық ыдырайтын орамалар.*

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РАЗРАБОТКА ВЫСОКОЭФФЕКТИВНЫХ СЪЕДОБНЫХ ПЛЕНОК ИЗ НАТУРАЛЬНЫХ КРАХМАЛОВ: ИССЛЕДОВАНИЕ БАРЬЕРНЫХ, МЕХАНИЧЕСКИХ И РАСТВОРИМЫХ СВОЙСТВ

Целью данного исследования было оценить физико-химические свойства съедобных плёнок, приготовленных на основе пяти видов крахмала – рисового, кассавы, кукурузного, картофельного и пшеничного – с использованием трёх пищевых пластификаторов: глицерина, сорбита и ксилита. Плёнки изготавливались методом литья из суспензии крахмала с добавлением пластификаторов, с последующей сушкой при контролируемых условиях. Проводились измерения водяной паропроницаемости (WVP), прочности на разрыв (TS), удлинения при разрыве (E%) и водорастворимости.

Результаты показали, что происхождение крахмала и тип пластификатора существенно влияют на все исследуемые характеристики. Плёнки на основе рисового и картофельного крахмала с сорбитом или ксилитом продемонстрировали низкую паропроницаемость и высокую прочность, что указывает на хорошие барьерные и механические свойства. В то же время плёнки из крахмала кассавы и кукурузы с глицерином обладали большей гибкостью, но худшей водостойкостью и прочностью.

Таким образом, свойства съедобных крахмальных плёнок можно адаптировать под конкретные задачи пищевой упаковки путём подбора соответствующих комбинаций крахмала и пластификатора. Исследование подтверждает потенциал использования местного сырья для разработки биоразлагаемой функциональной упаковки..

Ключевые слова: крахмальные плёнки; пластификатор; паропроницаемость; прочность на разрыв; растворимость; биоразлагаемая упаковка.

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