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Properties of Bioplastic Straws Made from Arrowroot Starch with Chitosan Additions

Shinta Mutia Sari*, Tuty Anggraini, Fauzan Azima

ABSTRACT

The growing environmental impact of plastic waste has sparked the development of alternative biodegradable materials. The purpose of this study is to assess the properties of bioplastic straws manufactured from arrowroot starch with various concentrations of chitosan (1%, 2%, 3%, and 4% as a strengthening agent). Arrowroot starch was used for its high amylose content (22.70%), which promotes film formation. The straws were made by blending gelatinized arrowroot starch with dissolved chitosan and glycerol as a plasticizer, then drying and shaping. The resulting bioplastic straws were tested for hardness, solubility, water absorption, biodegradability, and functional groups using FTIR and SEM. The results revealed that increasing the chitosan concentration had a substantial effect on the mechanical and functional qualities of the straws. The formulation with 3% chitosan performed the best in terms of hardness (4.11 N/cm^2), moderate solubility (37.55%), excellent water absorption (41.61%), and biodegradation (79.44%). FTIR spectra revealed the interaction of hydroxyl (−OH) groups in starch with amine (−NH$_2$) groups in chitosan, indicating a strong hydrogen bond. SEM scans revealed a tight and uniform surface structure in the 3% treatment, indicating structural integrity. The addition of chitosan effectively increased the straw's water resistance and mechanical strength. This study emphasizes the feasibility of using local agricultural resources to create ecologically friendly bioplastic straws.

Keywords: arrowroot starch, biodegradability, bioplastic, chitosan, straw

INTRODUCTION

Plastic straws are used daily around the world, with most of the waste ending up in the ocean, endangering marine ecosystems (Ni *et al*. 2024). In Indonesia, plastic trash is the second largest contributor to total waste, accounting for 19.34% in 2023. This environmental concern has prompted the creation of biodegradable alternatives, such as starch-based bioplastic straws. Arrowroot starch (*Maranta arundinacea* L.) is a promising local biopolymer with a high amylose content (22.70%) and outstanding film-forming properties (Nogueira *et al*. 2021; Setyaningrum & Adi 2022). However, starch-only films are fragile and have poor water resistance. Chitosan, a polysaccharide derived from crustacean shells, has excellent mechanical strength, barrier characteristics, and compatibility with starch matrices (Abera *et al*. 2024). The mixture of starch with chitosan enhances structural integrity and water resistance via hydrogen bonding interactions (Alimi *et al*. 2023). The purpose of this study was to assess the influence of various chitosan concentrations on the quality of arrowroot starch-based bioplastic straws and to identify the most effective formulation.

METHODS

The Biochemistry and Food Nutrition Laboratory, Faculty of Agricultural Technology, Andalas University, conducted this experiment from December 2024 to May 2025. Arrowroot starch, chitosan, 1% glycerol, acetic acid, distilled water, and silica gel were utilized as materials, and instruments included a blender, digital scale, hot plate stirrer, oven, Fourier Transformed Infrared (FTIR) spectrometer, Scanning Electron Microscope (SEM), texture analyzer, and silicone trays. The study employed a Completely Randomized Design (CRD) with four concentrations of chitosan: 1%, 2%, 3%, and 4% (w/v), with each treatment replicated four times.

Bioplastic Straw Preparation

Chitosan with concentrations according to treatments of 1% (K1), 2% (K2), 3% (K3), and 4% (K4) (w/v) was weighed and dissolved in 1% (v/v) acetic acid. The solution was heated at 75 ºC for 25 min while stirring continuously until the chitosan was completely dissolved. Separately, arrowroot starch (5% w/v) was weighed and dissolved in distilled water. The starch solution was heated to 75°C for 25 min while being

Food Science and Agricultural Product Technology Department, Faculty of Agricultural Technology, Andalas University, Padang 25613, Indonesia
* Corresponding Author:
  Email: shintamutiasari@pertanian.go.id

constantly stirred at 400 rpm on a hot plate stirrer until gelatinization occurred. The starch solution was then mixed with the previously prepared chitosan solution, followed by the addition of 1% (v/v) glycerol as a plasticizer. The mixture was reheated for 5 min while stirring continuously until it reached a viscous viscosity and there were no lumps. The resultant solution was poured into heat-resistant silicone molds and dried in a food dehydrator at 50°C for 6 h. After drying, the film was cooled for 15 min before peeling it off the silicone mold and rolling it to make bioplastic straws with stainless steel straw molds. The bioplastic straws were subsequently dried in a food dehydrator at 50°C for 6 h. To preserve moisture content and avoid water absorption, the finished items were stored in sealed plastic containers containing silica gel. The bioplastic straws were then analyzed further.

The study sought to determine the physical and functional features of the resulting bioplastic straws, such as hardness, solubility, water absorption, and biodegradability. FTIR was used to detect functional groups, whereas SEM was utilized to study surface morphology. The data were evaluated using Analysis of Variance (ANOVA), and if significant differences were found, Duncan's Multiple Range Test (DMRT) was used at a significance level of 5%.

Hardness

A Texture Analyzer was used to do the analysis. The bioplastic straw samples were placed on the testing platform, and the test began by pressing the start button on the device. The analyzer probe applied force to the sample and measured the peak force generated during compression. The samples' hardness was then determined using the following equation:

$$Hardness\ (N/cm2) = \frac{\left[\frac{peak\ load\ (g)}{1000}\right] \times 9.8}{probe\ diameter}$$

Solubility

The solubility test began by weighing the starting mass of the bioplastic straw sample (W_1). The sample was then submerged in 150 mL of distilled water at room temperature for 12 h. After immersion, the sample was dried in an oven at 105°C for 2 h, chilled in a desiccator for 10 min, and weighed again (W_2). The sample's solubility was estimated using the following equation (Savitri et al. 2024):

$$Solubility\ (\%) = (W_1 − W_2)/W_1 \times 100\%$$

Water Absorption

Before testing, the bioplastic straw samples were chopped into 2-cm segments. Each sample was weighed to calculate its starting mass (W_0). A 50 mL beaker containing 10 mL of distilled water was prepared, and the sample was immersed in the water at room temperature for one minute. Following immersion, the sample was extracted, drained to remove excess surface water, and weighed again (W_1). Water absorption was determined using the following equation (Lestari et al. 2023):

$$Water\ absorption\ (\%) = (W_1 − W_0)/W_0 \times 100\%$$

Biodegradation Test (Soil Burial Method)

The biodegradation test was carried out utilizing the soil burial method. Bioplastic straw samples were chopped into 3-cm lengths and weighed to measure their starting mass (W_0). The samples were then buried at a depth of 10 cm in soil and left for 6 d to degrade. Following the burial period, the samples were carefully retrieved from the soil, gently cleaned without causing structural damage, and weighed again (W_1). The weight loss was computed with the following equation (Anggraini et al. 2022):

$$Weight\ loss\ (\%) = = (W_0 − W_1)/W_0 \times 100\%$$

FTIR (Fourier Transform Infrared) Analysis

Functional group analysis was carried out using FTIR spectroscopy to identify chemical compounds based on the characteristic vibrations of functional groups found in straw samples. The analysis was carried out at room temperature using an FTIR spectrometer (PerkinElmer Frontier Optica FTIR, model FTIR-00-0515) in Attenuated Total Reflection (ATR) mode. Four sequential scans were used to record FTIR spectra in the 400−4000 cm^{-1} wavenumber region, with a resolution of 4 cm^{-1}. The operating premise of FTIR is based on molecule functional groups' capacity to absorb infrared radiation at specific wavelengths, resulting in distinct vibrational patterns. Each component, including arrowroot starch (−OH groups), chitosan (−NH$_2$ and −OH groups), and glycerol (−OH groups), has distinct infrared absorption bands. The FTIR spectra were then studied to see chemical interactions between the components and functional group alterations caused by the addition of chitosan at different doses (Xu et al. 2022).

SEM (Scanning Electron Microscopy)

Surface structure research was performed using SEM to examine the micro-morphology of the straw surface. Straw samples with the optimal treatment (based on parameter evaluations) were conditioned in an acrylic drying chamber at 25 ± 1°C and 52% ± 1% relative humidity for 72 ± 2 h. The samples were then frozen using liquid nitrogen until brittle and shattered, yielding cross-sectional fragments that were then reconditioned in the drying chamber at 25°C. Prior to observation, the sample surfaces were mounted on a holder and coated with a thin layer of gold under

vacuum to improve conductivity. Surface morphology and microstructural features were investigated with a Quanta 200 scanning electron microscope at a voltage of 1 kV and various magnifications (Xu *et al*. 2022).

RESULTS AND DISCUSSION

Hardness

The hardness ratings show the bioplastic straws' ability to endure external pressure before distortion or fracture. As shown in Table 1, the addition of chitosan greatly increased the hardness of the bioplastic straws, with a greater increase reported at higher doses. Treatments K1 and K2 had similar hardness values (0.52 and 0.37 N/cm^2, respectively), whereas K3 (4.11 N/cm^2) and K4 (4.81 N/cm^2) showed a substantial increase. These findings are consistent with prior research indicating that incorporating chitosan into starch-based materials increases mechanical strength by forming hydrogen bonds between chitosan amino groups and starch hydroxyl groups (Fan *et al*. 2023; Jati *et al*. 2023). Such interactions reduce porosity and produce a more compact polymer matrix, which improves mechanical integrity. However, at lower chitosan concentrations (K1 and K2), the restricted number of hydrogen bonding sites is inadequate to form a robust polymeric network, resulting in weaker and more fragile structures. This shows the existence of a critical concentration at which chitosan-starch interactions become optimum and significantly improve hardness.

In addition to reinforcing the polymer matrix, chitosan helps to regulate moisture levels within the straws. Its semi-crystalline and dense network decreases internal water migration, resulting in a stiffer material that is less susceptible to deformation under pressure (Sreelakshmi *et al*. 2024). This dual role, mechanical strengthening and moisture reduction, explains the considerable increase in hardness reported at higher chitosan levels. Practically speaking, increased hardness is critical for the functional performance of edible bioplastic straws. Adequate hardness ensures resistance to biting force, stirring in beverages, and deformation during use, bringing them closer to traditional plastic straws. Furthermore, the usage of biodegradable starch-chitosan composites has environmental benefits because these straws can minimize dependency on petroleum-based plastics while preserving adequate mechanical strength for consumer applications.

Solubility

As indicated in Table 2, the solubility analysis demonstrated that increasing the chitosan concentration decreased the solubility of bioplastic straws. Treatment K2 had the maximum solubility (40.42 ± 0.54%), whereas K4 had the lowest (32.89 ± 3.12%). This trend can be due to the denser polymer matrix generated at greater chitosan concentrations via hydrogen bonding interactions, which prevent water penetration and dissolution of the film structure. A similar phenomenon was described by Susilowati and Lestari (2019), that increased chitosan concentrations reduced the solubility of starch-based edible films.

Interestingly, the maximum solubility was found at K2, not in the control treatment or lowest chitosan concentration (K1). This shows that at intermediate concentrations, the polymer matrix was not yet dense enough to limit water diffusion, but chitosan's hydrophilic nature aided water uptake and dissolution. At this transitional stage, the quantity of intermolecular hydrogen bonds produced was inadequate to maintain the structure, resulting in increased solubility. In contrast, when the concentration increased (K3 and K4), stronger hydrogen bonding between chitosan and starch resulted in a tighter and more water-resistant matrix, lowering solubility. This pattern is consistent with previous research demonstrating that chitosan has dual behavior: it increases solubility at low-to-moderate concentrations due to its hydrophilicity but decreases solubility at higher concentrations due to network densification (Susilowati & Lestari 2019).

Table 1 Hardness of bioplastic straws

Percentage of chitosan	Hardness (N/cm^2)
1% (K1)	0.52 ± 0.01[a]
2% (K2)	0.37 ± 0.01[a]
3% (K3)	4.11 ± 0.11[b]
4% (K4)	4.81 ± 0.18[c]

Remark: Values followed by different superscript letters differ significantly (DNMRT, $p < 0.05$).

Table 2 Solubility of bioplastic straws

Percentage of chitosan	Solubility (%)
1% (K1)	38.37 ± 2.06[bc]
2% (K2)	40.42 ± 0.54[c]
3% (K3)	37.55 ± 1.18[b]
4% (K4)	32.89 ± 3.12[a]

Remark: Values followed by different superscript letters differ significantly (DNMRT, $p < 0.05$).

In comparison to a commercial starch-based straw (StrawMe) constructed from rice and maize starch, which had a solubility of just 11.13 ± 0.11%, the arrowroot starch-chitosan straws in this investigation had much better solubility values of 32.89−40.42%. The commercial product's lower solubility is most likely caused by the addition of reinforcing materials such as cellulose fibers, hydrophobic polymers, or protective coatings, which improve water resistance and structural integrity during usage. This contrast illustrates that, whereas arrowroot starch-chitosan straws are more biodegradable due to their increased solubility, they are less water resistant than commercial alternatives.

Solubility serves two purposes in applications. High solubility might be beneficial to the environment because it speeds up biodegradation and decreases persistence in natural ecosystems (Savitri et al. 2024). Excess solubility, on the other hand, may jeopardize product performance by lowering straw durability in watery settings, particularly with prolonged usage in beverages. For industrial applications, it is vital to strike a balance between solubility and appropriate water resistance. Optimizing composition, such as mixing arrowroot starch with strengthening biopolymers or coatings, could improve the straws' practical functioning while keeping them biodegradable.

Water Absorption

The water absorption capacity of arrowroot starch-based bioplastic straws with various chitosan concentrations is presented in Table 3. Chitosan content has a substantial effect on the water absorption of arrowroot starch-based straws. The lowest absorption was found at 1% chitosan (K1: 38.20 ± 0.96%), indicating better structural stability in wet environments. This shows that low quantities of chitosan strengthen the polymer network, avoiding excessive swelling and increasing straw durability throughout usage. However, 4% chitosan (K4: 48.83 ± 1.10%) had the maximum absorption, indicating a lower resistance to water penetration and reduced structural integrity in wet environments. Importantly, all

treatments remained within the maximum swelling capacity (70%) set by Japanese Industrial Standards (JIS) for bioplastics (Lestari et al. 2023).

Compared to the commercial straw (30.77 ± 0.64%), the experimental straws had increased water absorption. This distinction could be attributable to the use of glycerol as a plasticizer in the proposed formulation, which, due to its hygroscopic nature, promotes water uptake (Khairati 2022). In contrast, commercial straws are frequently strengthened with cellulose strands or coated to improve water resistance. The overall trend suggests that increasing chitosan content improves water absorption. This is consistent with prior studies that increased chitosan levels increase hydrophilicity due to its hydroxyl ($-OH$) and amino ($-NH_2$) groups, which easily form hydrogen bonds with water molecules (Chau et al. 2024). At moderate concentrations (1−3%), chitosan strengthens the starch-polymer matrix via intermolecular interactions, resulting in a more compact structure that restricts water penetration. This explains why K3 (3% chitosan) exhibited a decrease compared to K2. However, at high levels (4%), chitosan can disrupt matrix homogeneity, resulting in aggregate formation, increased porosity, and more water absorption (Silvestre et al. 2021).

Biodegradability

Biodegradation was assessed by weight loss after 6 days of soil burial, with findings ranging from 54.72% to 79.44% (Table 4). K3 showed much higher degradation (79.44 ± 8.48%) compared to other treatments, while K2 had the lowest value (54.72 ± 1.44%). The findings suggest that chitosan concentration did not have a strictly linear effect on biodegradation. Weight loss at 2% (K2) was lower than at K1, most likely due to chitosan's film-forming activity, which creates a tighter, more compact matrix that hinders water and microbial enzyme transport. Similar findings were published by Fan et al. (2023), that denser matrices restrict microbial accessibility, lowering breakdown rates.

The K3 treatment, on the other hand, showed the most degradation, implying that at this concentration,

Table 3 Water absorption capacity of bioplastic straws

Percentage of chitosan	Water absorption (%)
1% (K1)	38.20 ± 0.96[a]
2% (K2)	42.59 ± 1.42[b]
3% (K3)	41.61 ± 0.77[b]
4% (K4)	48.83 ± 1.10[c]

Remark: Values followed by different superscript letters differ significantly (DNMRT, $p < 0.05$).

Table 4 Weight loss of bioplastic straws

Percentage of chitosan	Weight loss (%)
1% (K1)	62.58 ± 5.14[ab]
2% (K2)	54.72 ± 1.44[a]
3% (K3)	79.44 ± 8.48[c]
4% (K4)	74.59 ± 8.77[bc]

Remark: Values followed by different superscript letters differ significantly (DNMRT, $p < 0.05$).

chitosan was more uniformly distributed throughout the starch-glycerol matrix, resulting in a structure with sufficient mechanical strength while allowing for porosity and intermolecular spacing. This improved biodegradability by allowing water and microbes to penetrate more easily. Homogeneous additive distribution has been shown to improve biodegradation by creating diffusion channels for oxygen and moisture (Suryani *et al*. 2021). The following decrease at K4 supports the theory of over-crosslinking between chitosan and starch hydroxyl groups, resulting in a denser network with lower porosity and microbial accessibility. Excessive chitosan may also increase antibacterial activity, further inhibiting microbial action (Fan *et al*. 2023).

The main formulation components have an additional effect on biodegradation behavior. Arrowroot starch, a natural polymer, is easily broken down by soil microbes (Abdillah *et al*. 2024). Glycerol, as a hydrophilic plasticizer, increases water absorption, softening, and fragmentation, hastening biodegradation (Abera *et al*. 2024). Importantly, all treatments resulted in more than 50% weight loss after 6 d, suggesting that the created straws are highly biodegradable and fulfill the basic standards for environmentally friendly packaging. Among the investigated formulations, 3% chitosan provided the best balance, enhancing biodegradation while retaining structural integrity.

FTIR Analysis

FTIR analysis was used to detect functional groups and molecular interactions in bioplastic straws with varying chitosan concentrations. All samples showed a large peak at 3291−3296 cm^{-1} due to O−H stretching, demonstrating hydrogen bonding in the starch−chitosan matrix (Figure 1). Peaks at 2925−2929 cm^{-1} indicated aliphatic C−H stretching. The N−H bending from chitosan's amine group appeared between 1591 and 1599 cm^{-1}, with 3% chitosan having a lower transmittance, indicating greater hydrogen bonding. Notably, a distinct band at 1980 cm^{-1} occurred solely in the 3% chitosan sample, which could indicate special chemical interactions or overtone vibrations created at the appropriate ratio. Peaks at 1010−1015 cm^{-1} indicated C−O−C stretching of the starch backbone. The overall spectra revealed that increasing chitosan content increased intermolecular contacts, especially at 3%, resulting in the most stable and homogeneous matrix structure.

The FTIR spectrum results in this work are consistent with previous publications that show intermolecular interactions between starch and chitosan via hydrogen bonding and the creation of new reactive groups. According to Alimi *et al*. (2023), a large absorption band in the 3600−3000 cm^{-1} range represents the stretching vibrations of −OH and −NH$_2$ groups, demonstrating complicated hydrogen interactions between starch hydroxyl groups and chitosan amine groups. This band is typical of hydrophilic polysaccharide-based films, such as chitosan and starch, which are connected via intra- and intermolecular networks.

SEM Analysis

SEM was used at 10,000× magnification to analyze the surface morphology of bioplastic straws. The 3% chitosan treatment resulted in a relatively compact, smooth, and homogeneous surface with few obvious fractures or pores (Figure 2). This implies that arrowroot starch and chitosan are compatible and interact well within the polymer matrix. The dense structure observed is consistent with the improved mechanical characteristics and water resistance found
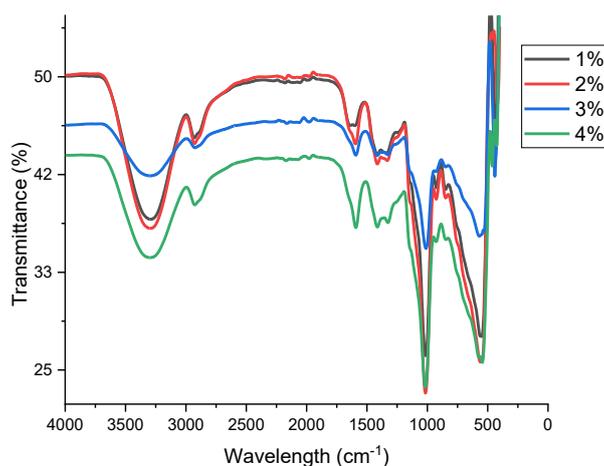

Figure 1 Fourier Transformed Infrared (FTIR) spectra of bioplastic straws at different chitosan concentrations.
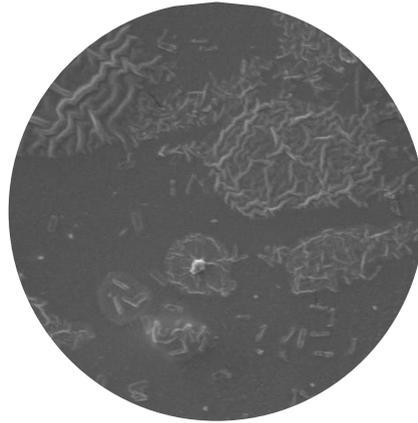
Figure 2 Scanning Electron Microscope (SEM) micrograph of bioplastic straw with 3% chitosan at 10,000× magnification.

in the 3% chitosan sample. These findings are consistent with Alimi *et al*. (2023), that incorporating chitosan into starch-based films results in denser and more uniform morphologies due to strong intermolecular hydrogen bonding. The absence of major surface flaws indicates appropriate film formation and phase stability, which contributes to improved biodegradability and product integrity after application.

CONCLUSION

After six days, arrowroot starch-based bioplastic straws with chitosan inclusion had hardness values ranging from 0.37 to 4.81 N/cm^2, water absorption of 38.20 to 48.83%, solubility of 32.89 to 40.42%, and biodegradation rates of 54.72 to 79.44%. The optimal performance was achieved with 3% chitosan, which gave excellent mechanical strength, low solubility, balanced water absorption, and the fastest degradation rate. FTIR validated hydrogen bonding between starch, chitosan, and glycerol, while SEM demonstrated a compact but porous shape that supported both functional characteristics and biodegradability. These data indicate that 3% chitosan is the most effective formulation, with promise for sustainable straw uses. Further research should focus on extended biodegradation, surface modification to minimize water intake, and industrial scalability.

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