MECHANICAL PROPERTIES OF MOCAF AND SAGO STARCH GELS WITH THE ADDITION OF SUCROSE AND D-ALLULOSE IN COLD STORAGE

UNDERGRADUATE THESIS

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ORIGINALITY STATEMENT OF UNDERGRADUATE THESIS

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Hereby declare that :

1. The undergraduate thesis entitled "MECHANICAL PROPERTIES OF MOCAF AND SAGO STARCH GELS WITH THE ADDITION OF SUCROSE AND D-ALLULOSE IN COLD STORAGE" and the research related to this thesis are entirely my own work.
2. Every idea or quotation from the work of other authors, whether in the form of publications or other sources included in this thesis, has been properly acknowledged in accordance with academic and scientific writing standards.
3. The author also acknowledges that this thesis could be completed with the full guidance and support of the supervisors, namely Ahmad Ni'matullah Al-Baarri, S.Pt., M.P., Ph.D. and Masagus Haidir Tamimi, S.T.P., M.Sc.

Should any evidence of academic misconduct or plagiarism be discovered in the future regarding this thesis, the author is willing to accept any academic sanctions imposed, including the revocation of the bachelor's degree obtained, in accordance with the regulations of the Undergraduate Program of Food Technology, Faculty of Animal and Agricultural Sciences, Diponegoro University.

Semarang, June 2026
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SUMMARY

AILSA OCHA ALIFA. 23020122130074. 2026. Mechanical Properties Of Mocaf And Sago Starch Gels With The Addition Of Sucrose And D-Allulose In Cold Storage (Supervisor: **AHMAD NI'MATULLAH AL-BAARRI** and **MASAGUS HAIDIR TAMIMI**).

Starch gels are widely used in food products, and their mechanical properties during storage are I mportant for determining product texture and quality. Sucrose is commonly used to modify gel characteristics; however, growing interest in healthier sugar alternatives has increased attention toward D-allulose, a rare sugar that provides similar sweetness with lower caloric value. Therefore, there is a need to explore healthier sugar alternatives for starch-based gel systems while maintaining desirable mechanical properties, with D-allulose considered a promising alternative.

This research was conducted from November 2025 to May 2026 at the Food Protein Functionalities Laboratory, Faculty of Agriculture, Kagawa University, Japan, and the Integrated Laboratory of Diponegoro University. The study investigated the effects of D-allulose on the mechanical properties of MOCAF and sago starch gels during cold storage in comparison with sucrose. Starch gels were prepared with three treatments: control, sucrose, and D-allulose, with sugar added at 10% (w/w) of the starch. The gels were stored at 4 ± 0.5 °C and analyzed on Days 1, 2, and 3. Mechanical properties, including maximum load, fracture strain, and elastic modulus, were determined using a creep meter. Results are presented as mean ± standard deviation of three independent replicates.

The mechanical properties of both MOCAF and sago starch gels changed during storage because of structural reorganization and retrogradation. In MOCAF gels, sucrose generally produced higher maximum load and elastic modulus, indicating a stronger and stiffer gel network, whereas D-allulose resulted in relatively higher fracture strain, indicating greater deformability. In sago gels, all treatments showed increased stiffness during storage, although the effects of sugar addition were less pronounced than in MOCAF gels, indicating that the response depended on the starch source.

Overall, sucrose and D-allulose affected starch gel properties differently. Sucrose generally promoted a more stable and rigid gel structure, whereas D-allulose produced a different balance between strength, stiffness, and deformability. These findings suggest that D-allulose should be regarded as a distinct modifier of starch gel behavior rather than a direct functional substitute for sucrose in MOCAF and sago starch gel systems.

PREFACE

Praise and gratitude are devoted to Allah SWT for all blessings, mercy, and guidance bestowed upon the author, enabling the completion of this undergraduate thesis entitled *"Mechanical Properties of MOCAF and Sago Starch Gels with the Addition of Sucrose and D-Allulose in Cold Storage"* in a timely manner.

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but to carry, *seseorang yang selalu merayu tuhannya untuk bisa menjadi salah satu bagian dari mahasiwa setidaknya di Undip yang sebenarnya masuk kesini saja berdarah darah, seseorang yang harus mau tidak mau mengubur mimpi lainnya. Apa yang dipersembahkan disini kepada orang tua dan keluarga, baru kemudian dirinya—setelah berupaya berkali kali dari orang lainnya karena selalu merasa menjadi nomor terakhir di dalam ruangan, setelah memikul segala harapan yang didapatkan, setelah sebisanya berusaha, terdengar klise.* Think big, that's what we are—what we believe.

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The author realizes that this undergraduate thesis is still far from perfect in terms of both technical writing and content. Therefore, constructive criticism, suggestions, and feedback are sincerely welcomed for future improvement. The author hopes that this thesis will provide benefits for the author, academic institutions, and readers in general.

Semarang, June 2026

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CHAPTER I

INTRODUCTION

1.1. Background

Starch is a major carbohydrate source widely consumed by the Indonesian population and plays an important role as a raw material in the food industry. Indonesians rely heavily on starch sources such as rice and wheat (Saputra & Setyowati, 2024), as well as tubers, which function not only as energy sources but also as texture formers and gelling agents in processed food products (Natalia et al., 2022). Nevertheless, starch has limitations to temperature and storage time. Storage duration can affect the texture and structure of starch itself, leading to undesirable changes in organoleptic properties (Syahbanu et al., 2023).

In recent decades, food diversification has become a strategic issue in Indonesia. The aim of diversification is to reduce dependence on a single staple food, strengthen food security, and optimize the use of underutilized local resources (Defri et al., 2022). One local food material with great potential is sago (*Metroxylon sagu*), which has the largest cultivation area in the world, approximately 1.128 million hectares (Bintoro et al., 2018) and is recognized as a commodity highly adaptive to environmental changes (Bintuni et al., 2026). Sago is a traditional starch source in eastern Indonesia, widely found in Papua, West Papua, South Papua, Southwest Papua, Maluku, Sulawesi, and parts of Kalimantan (Dimara et al., 2021). With its high starch content (Moshawih et al., 2025), sago has strong potential as a carbohydrate-rich food material. Demand for sago starch in both local and global

markets continues to increase, driven by its versatility as a food source and favorable functional characteristics (Moshawih et al., 2025).

Modified Cassava Flour (MOCAF) is a fermented cassava flour increasingly used as an alternative starch source in the food industry (Khasanah et al., 2024; Oyeyinka et al., 2020). Generally, fermentation improves functional properties, producing flour with a whiter color, more neutral aroma, and better performance in food applications, particularly as a flexible alternative starch that can substitute wheat flour (Khasanah et al., 2024). This makes MOCAF a promising substitute for wheat flour in various gluten-free products currently under development, such as bread, cakes, noodles, and other items. In Indonesia, cassava is the raw material for MOCAF, abundantly cultivated in regions such as Lampung, Central Java, East Java, West Java, and Gunung Kidul Yogyakarta.

With high raw material availability, Indonesia ranks as the fourth largest cassava producer globally (Widowati et al., 2025). Combined with relatively simple processing, MOCAF stands out as a potential local food alternative. Moreover, the growing global trend toward healthy foods such as gluten-free, allergen-free products with dietary fiber and resistant starch further strengthens MOCAF's market potential (Paksi et al., 2025). Thus, both sago and MOCAF hold significant promise as starch sources, developing food products based on local raw materials.

Despite their potential, starches from sago and MOCAF are not entirely stable during storage (Syahbanu et al., 2023). After gelatinization, starch undergoes structural changes during storage, particularly under low temperature conditions (S. Yang et al., 2021). The progression of these changes may be influenced by the

presence of sugars. Sucrose is frequently used in starch gel studies due to its widespread application in food systems and well-established interactions with starch. Consequently, it serves as a standard reference for assessing starch gel properties. D-allulose reported more effective than sucrose in inhibiting the hardening of amylopectin rich starch gels during refrigerated storage due to its ability to promote looser hydrogen bond interactions and limit the tight realignment of starch chains (Kwakye et al., 2024). Although the effects of D-allulose on several starch systems have been reported, its influence on MOCAF and sago starch gels in comparison with sucrose remains unclear. Considering the growing interest in utilizing indigenous starch resources, understanding the behavior of these two starches is essential for their broader food applications.

1.2. Research Objectives and Significance of the Study

This study aims to investigate the effects of D-allulose addition to sago and MOCAF starch gels during storage, in comparison with the commercial sugar sucrose. The benefit of this research is to determine the comparative influence of D-allulose and sucrose on the stability and properties of sago and MOCAF gels during storage.

CHAPTER II

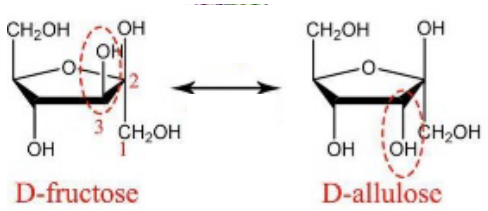
LITERATURE REVIEW

2.1. D-Allulose

D-allulose, also known as D-psicose, is a rare sugar that has recently attracted considerable attention as a functional sweetener in the food industry. It is classified as a monosaccharide and a C-3 epimer of D-fructose, naturally occurring only in very small quantities (Kwakye et al., 2024). Compared with sucrose, D-allulose provides approximately 70% of the sweetness, offers a clean, mild taste and a cooling sensation without the bitterness associated with many other sweeteners, while contributing only about 0.2 to 0.4 kcal/g, less than 10% of the calories found in sucrose or fructose (4 kcal/g), making it an attractive low-calorie sweetener (W. Zhang et al., 2023).

D-Allulose naturally occurs only in trace amounts (less than 0.15%) in various food sources, including wheat, raisins, dried figs, and kiwi, as well as processed products such as brown sugar, cane molasses, and Worcestershire sauce. Under normal conditions, it appears as a white, odorless powder with high water solubility, reaching approximately 291 g per 100 g of water at room temperature. These characteristics contribute to its suitability for a wide range of food applications (Zhao et al., 2025). Owing to its safety and functional properties, D-allulose has been recognized as Generally Recognized as Safe (GRAS) by the U.S. Food and Drug Administration (FDA) and has been increasingly explored as a healthier alternative to conventional sugars (Kwakye et al., 2024). In the United

States, it is excluded from the "total added sugars" count on nutrition labels (Woodbury & Mauer, 2023).



Ilustration 1. Structural comparison of D-fructose and D-allulose.

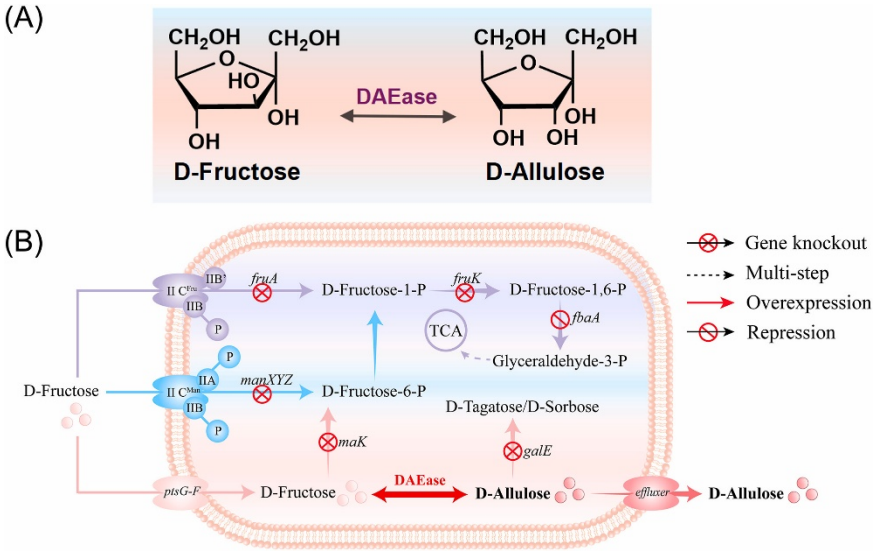
Sources: (J. Li et al., 2025)

Beyond its sweetening ability, D-allulose exhibits several physiological benefits that distinguish it from conventional sugars. Previous studies have reported that D-allulose helps regulate blood glucose and insulin levels without markedly affecting blood lipid profiles (Das et al., 2024). In addition, it has been associated with anti-obesity effects by promoting fat oxidation, reducing lipid accumulation, and suppressing appetite. D-allulose has also been reported to possess antioxidant properties and improve cholesterol metabolism, supporting its classification as a functional sweetener rather than merely a sugar substitute (Das et al., 2024). These physiological advantages have encouraged its application in various food products while maintaining desirable sensory characteristics.

In addition to its nutritional benefits, D-allulose exhibits unique physicochemical properties that influence starch-based systems. Unlike sucrose, D-allulose allows starch gelatinization to occur at relatively lower temperatures, which may help preserve heat-sensitive food components during thermal processing (Das et al., 2024). Furthermore, D-allulose has been reported to inhibit starch hardening during refrigerated storage, particularly in amylopectin-rich starches. This effect is associated with its ability to promote the formation of looser hydrogen bonds,

thereby reducing the tight reassociation of starch chains and producing a more porous and flexible gel network (Kwakye et al., 2024). As a result, starch gels containing D-allulose generally exhibit improved softness and structural stability during storage.

The influence of D-allulose on starch functionality is also closely related to its interaction with water. Due to its high hydrophilicity, D-allulose possesses a greater water-holding capacity than sucrose, enabling it to retain moisture more effectively within starch gel systems (Kwakye et al., 2024; Z. Wang et al., 2024). This property contributes to reduced moisture loss and delayed textural deterioration during storage, thereby helping maintain the quality of starch-based products over time.



Ilustration 2. Biosynthetic pathway of D-allulose from D-fructose through D-allulose 3-epimerase (DAEase).

Sources: (Zhu et al., 2026)

The limited natural abundance of D-allulose has encouraged the development of efficient biotechnological production methods. Since D-allulose

occurs only in trace amounts in natural sources, direct extraction is considered economically impractical. Therefore, commercial production primarily relies on enzymatic conversion and microbial fermentation. One of the most widely used approaches is the Izumoring strategy, in which D-fructose is converted into D-allulose by D-allulose-3-epimerase (DAEase) (Zhao et al., 2025). This reversible enzymatic reaction generally achieves a conversion rate of approximately 30% (Zhao et al., 2025; Zhu et al., 2026).

In addition to enzymatic conversion, microbial fermentation has been developed using engineered microorganisms such as *Escherichia coli* and *Bacillus subtilis* to biosynthesize D-allulose from low-cost carbon sources, including glucose, sucrose, glycerol, and agricultural by-products (Zhao et al., 2025). Recent advances have also explored more sustainable production systems, including the utilization of agricultural waste as feedstocks to improve production efficiency while reducing manufacturing costs (Zhao et al., 2025). These technological developments have enhanced the commercial availability of D-allulose and supported its wider application in the food industry.

The improved availability of D-allulose, together with its favorable physicochemical and physiological properties, has promoted its application in a wide range of food products. In bakery products such as pound cakes, muffins, and cookies, D-allulose is used as a low-calorie sweetener while improving coloration and delaying staling during storage (Das et al., 2024). It accelerates the Maillard reaction, leading to darker, redder crust colours and richer aromas than with sucrose; however, it may result in less volume expansion and more compact

textures if baking times are not adjusted (Zhao et al., 2025). In addition, D-allulose has been incorporated into functional beverages because of its high solubility and processing stability, as well as dairy products such as yogurt to improve sensory quality and antioxidant capacity (Das et al., 2024). It has a greater water-holding ability than sucrose, which helps maintain freshness in yeast-baked products but can lead to lower water activity in the final product (Bolger et al., 2021). These diverse applications demonstrate the potential of D-allulose as a multifunctional ingredient in food systems.

2.2. Sucrose

Sucrose, commonly known as table sugar, is one of the most widely used sweeteners in the food industry because of its sweetening, bulking, and structural properties. It is classified as a disaccharide consisting of one D-glucose and one D-fructose molecule (L. Wang et al., 2016; Zhao et al., 2025) linked by an α-1,2 glycosidic bond, with a molecular formula of $C_{12}H_{22}O_{11}$ (Z. Wang et al., 2024). Sucrose serves as the reference sweetener with a relative sweetness value of 1.0 and provides approximately 4 kcal/g. Despite its desirable functional properties, excessive sucrose consumption has been associated with an increased risk of obesity, diabetes mellitus, and cardiovascular diseases, leading to growing interest in alternative sweeteners (Kwakye et al., 2024).

In addition to its sensory properties, sucrose possesses physicochemical characteristics that influence its functionality in food systems. Sucrose is highly soluble in water (Woodbury et al., 2023) and contains numerous equatorial

hydroxyl (-OH) groups capable of forming extensive hydrogen bonds with water and polysaccharides (Allan & Mauer, 2022). In aqueous systems, sucrose molecules also form intramolecular hydrogen bonds between their glucose and fructose moieties, influencing their interactions with surrounding polymers, make them less available to interact with other polymers compared to monosaccharides like allulose (Kwakye et al., 2024). These characteristics contribute to the ability of sucrose to modify water distribution and molecular interactions in starch-based systems.

Sucrose is widely recognized as an important functional ingredient that influences the thermal and mechanical behavior of starch. Previous studies have reported that sucrose substantially increases starch gelatinization and pasting temperatures by restricting starch chain mobility and stabilizing starch granules (Kitagawa et al., 2025). At higher concentrations, sucrose also limits starch granule swelling and reduces amylose leaching, resulting in lower paste viscosity (Woodbury et al., 2023). Its effect on starch retrogradation is concentration-dependent, acting as a retrogradation inhibitor at relatively low concentrations (10–20%) (Allan & Mauer, 2022; Zhao et al., 2025) while promoting retrogradation at higher concentrations (≥40%) due to the preservation of residual molecular order that facilitates crystal formation (Zhao et al., 2025). Furthermore, sucrose has been proposed to form "starch–sugar–starch" bridges, reinforcing the internal gel network while producing a relatively rigid gel structure.

Owing to these functional properties, sucrose has been extensively applied in a wide range of food products. It is commonly incorporated into bakery products (i.e white bread and muffins (15% concentration), pastries (30%), cakes (45%), and

cookies (≥60%)) (Woodbury et al., 2023; Woodbury & Mauer, 2023), confectionery as a primary gelling agent and sweetener in candies and chocolates (Ilhan et al., 2020), dairy products as a stabilizer in yogurts to improve firmness and consistency (Shoukat et al., 2025), and various processed foods to provide sweetness, improve texture, and enhance product stability. In starch-based foods, sucrose is frequently used as a reference sugar because its interactions with starch have been extensively characterized. Therefore, comparisons between sucrose and alternative sweeteners, such as D-allulose, are essential for understanding differences in starch gel behavior and functionality.

2.3. MOCAF

Modified Cassava Flour (MOCAF) is a fermented cassava-based flour produced from whole cassava roots (*Manihot esculenta* Crantz) through controlled microbial fermentation. It has been developed as an agro-industrial innovation to improve the functional and nutritional properties of native cassava flour while serving as a potential substitute for wheat flour in various food products (Paksi et al., 2025). Unlike conventional cassava flour, MOCAF undergoes biological modification, most commonly using lactic acid bacteria (LAB), particularly *Lactobacillus plantarum*, although yeasts and molds may also be employed during fermentation (Khasanah et al., 2024). In addition to microbial fermentation, starch modification can also be achieved by incorporating purified enzymes such as amylases and transferases, which directly alter starch molecular structures (Compart, J., Singh, A., Fettke, J., & Apriyanto, 2023; Ji et al., 2026). Among these

approaches, fermentation is considered a safe and environmentally friendly ("green") modification method because it improves flour functionality through natural enzymatic reactions while preserving product safety (Oyeyinka et al., 2020).

During fermentation, microorganisms produce cellulolytic and pectinolytic enzymes that degrade the cassava cell wall matrix and modify starch granules. These enzymatic activities generate fissures, pores, and rougher granule surfaces by partially disrupting the amylopectin structure (Oyeyinka et al., 2020; Putri et al., 2022), thereby increasing starch accessibility and altering its molecular organization (Khasanah et al., 2024). In addition to improving starch functionality, fermentation serves an important detoxification role by hydrolyzing cyanogenic glycosides and releasing hydrogen cyanide gas, reducing the cyanide content of cassava roots by more than 90% (Martínez et al., 2024; Oyeyinka et al., 2020). Consequently, the fermentation process not only enhances food safety but also produces flour with physicochemical characteristics that differ substantially from those of conventional cassava flour.

The structural modifications occurring during fermentation significantly influence the physicochemical properties of MOCAF. Compared with native cassava flour, MOCAF generally exhibits improved viscosity, water-holding capacity, rehydration ability, gelation properties, and solubility (Putri et al., 2022). These improvements are associated with changes in starch composition and granule morphology induced by microbial enzymatic activity. MOCAF typically contains approximately 83–87% starch, which is higher than that of conventional cassava flour (Khasanah et al., 2024). Fermentation also alters the amylose-to-amylopectin

ratio, reducing amylose content from approximately 27% to 24–26% as fermentation time increases (Oyeyinka et al., 2020). Because amylose and amylopectin contribute differently to starch functionality, these compositional changes play an important role in determining the rheological and mechanical behavior of MOCAF gels.

The modification process also influences the thermal behavior and pasting characteristics of MOCAF. Fermented cassava starch generally gelatinizes more readily than wheat starch, exhibiting relatively lower gelatinization and pasting temperatures (Anggraeni et al., 2024). In addition, fermentation decreases peak and breakdown viscosities while increasing final and setback viscosities (Oyeyinka et al., 2020), indicating a greater tendency for starch reassociation and retrogradation after gelatinization. The pasting behavior of MOCAF is also highly dependent on environmental conditions, particularly pH (Putri et al., 2022). Under acidic conditions, MOCAF exhibits higher peak viscosity and breakdown but lower viscosity stability, allowing gelatinization to occur more rapidly and with lower energy input (Putri et al., 2022). These findings demonstrate that fermentation not only modifies starch structure but also alters the processing characteristics of MOCAF in food systems (Oyeyinka et al., 2020).

Beyond its physicochemical properties, MOCAF has attracted considerable attention because of its nutritional and functional advantages. As a naturally gluten-free and hypoallergenic flour (Paksi et al., 2025), MOCAF is suitable for consumers with gluten intolerance or celiac disease. It also retains dietary fiber and resistant starch, which contribute to improved gut microbiota diversity and digestive health

(Paksi et al., 2025). Previous studies have reported that partial substitution of wheat flour with MOCAF can reduce postprandial blood glucose responses while improving satiety, indicating its potential application in foods intended for individuals with metabolic disorders such as type 2 diabetes (Paksi et al., 2025). Furthermore, MOCAF can replace up to 20% of wheat flour in bread formulations without significantly affecting sensory acceptance while increasing dietary fiber and mineral contents (Martínez et al., 2024) , and substitution levels of up to 40% have been successfully applied in several processed food products (Paksi et al., 2025).

The favorable functional properties of MOCAF have encouraged its application in a wide range of food products and strengthened its economic importance, particularly in Indonesia (Paksi et al., 2025). MOCAF has been utilized in noodles, bakery products, cookies, cakes, and various semi-moist foods because of its desirable functional characteristics and gluten-free nature (Putri et al., 2022). As Indonesia remains highly dependent on imported wheat, MOCAF has been recognized as a strategic local alternative capable of supporting national food diversification programs. In addition, increasing international demand for gluten-free and sustainable food ingredients has expanded the export potential of MOCAF, particularly in European and Middle Eastern markets (Paksi et al., 2025). Continuous improvements in fermentation technology, product standardization, and digital traceability are expected to further enhance the commercial competitiveness of MOCAF in both domestic and international markets.

2.4. Sago

Sago starch is a local starch source extracted from the trunk of the sago palm (*Metroxylon sagu* Rottb.), a monocotyledonous species belonging to the family Arecaceae (Ehara et al., 2018; Moshawih et al., 2025). It is widely recognized as one of the most productive starch crops in the world because of its exceptional starch yield per unit area, producing up to 25 tons of starch per hectare annually (Ehara et al., 2018; Moshawih et al., 2025). Native to tropical Southeast Asia and Melanesia, sago is extensively distributed in Indonesia, Papua New Guinea, and Malaysia (Moshawih et al., 2025), with Indonesia accounting for approximately 85% of the world's sago resources (Bintoro et al., 2018). Unlike many conventional starch crops, sago thrives in swampy and peatland environments where other crops cannot be cultivated economically, making it an important indigenous starch resource for sustainable food production (Moshawih et al., 2025). In Indonesia, sago has long served as a staple food, particularly in eastern regions such as Papua, Maluku, and Sulawesi (Bintoro et al., 2018).

The growing interest in sago starch is attributed not only to its abundance but also to its favorable physicochemical characteristics. Sago starch contains approximately 84.7 g carbohydrate per 100 g and consists predominantly of amylopectin with a smaller proportion of amylose (Moshawih et al., 2025; Okazaki, 2018). However, the amylose content varies depending on cultivar and growing conditions. White sago from Bogor contains approximately 26.11% amylose, whereas red sago from Jayapura contains around 24.07% (Du et al., 2020). During the "Angau Muda" developmental stage, amylose content has been reported to reach

29.4–31.2% (Moshawih et al., 2025). These compositional differences contribute to variations in starch functionality and processing behavior among different sago varieties.

The molecular composition of sago starch is closely associated with its granular structure and physicochemical properties. Sago starch granules are generally oval, ellipsoidal, or bell-shaped with relatively large diameters ranging from approximately 30 to 37.6 μm (Moshawih et al., 2025). They exhibit a C-type crystalline structure, representing a combination of A-type and B-type crystallinity with an overall crystallinity of approximately 28–32% (Moshawih et al., 2025). These structural characteristics influence water absorption, swelling behavior, gelatinization, and gel formation. In particular, the relatively high amylose content contributes to greater intermolecular association after gelatinization, making sago starch more susceptible to retrogradation than starches containing lower amylose levels (Park et al., 2020).

The thermal and pasting properties of sago starch further distinguish it from other starch sources. Sago starch typically gelatinizes at temperatures ranging from approximately 69.4 to 70.1 °C (Ehara et al., 2018), while its pasting temperature generally ranges between 72 and 80 °C depending on the variety (X. Wang et al., 2022). It also produces highly viscous pastes with excellent resistance to heat and shear (Du et al., 2020), characteristics that make sago starch suitable for products requiring stable gel structures. Nevertheless, its relatively high amylose content promotes molecular reassociation during storage, resulting in increased retrogradation and progressive changes in gel texture. Previous studies have shown

that starches with higher amylose concentrations exhibit stronger intermolecular hydrogen bonding, producing firmer gels but lower swelling capacity and reduced flexibility (Du et al., 2020). Conversely, starches containing lower amylose levels generally exhibit greater swelling and softer gel structures.

In addition to its functional properties, sago starch has attracted increasing attention because of its nutritional and industrial potential. Sago is naturally gluten-free and contains resistant starch that contributes to a relatively low glycemic index compared with many conventional carbohydrate sources. Resistant starch also functions as a prebiotic, promoting beneficial gut microbiota and moderating postprandial blood glucose responses (Moshawih et al., 2025). Owing to these nutritional characteristics together with its desirable physicochemical properties, sago starch has been widely utilized as a thickener, stabilizer, and gelling agent in noodles, confectionery products, bakery products, and various starch-based foods. Compared with cassava and corn starch, sago starch is capable of producing clearer gels with a chewier texture, making it attractive for numerous food applications (Ehara et al., 2018).

2.5. Starch Gelatinisation and Retrogradation

Gelatinisation started with the water and heat contact the starch granules followed by the granule swelling, loss of crystallinity, and effected to the amylose leaching due to the starch granules rupture and finally releasing their remaining contents. Gelatinisation can be influence by the sugar adding, generally increase the temperature of starch gelatinisation and modify gelatinisation enthalpy (C. Li,

2022), particulary interacting with amylose chains and slowing down the leaching (S. Li et al., 2024).

Retrodegradation occurs after starch recrystallizes overtime during cooling and storage. Retrogradation is an associate of the post-storage properties. Amylose retrogrades rapidly, forming firm gels, however amylopectin retrogrades slower, contributing to staling in bread and other starch-rich foods (S. Li et al., 2024). Sugars modify starch retrogradation by forming hydrogen bonds with water molecules, thereby competing with starch chains for available water and reducing starch-starch chain interactions that drive recrystallization. Low molecular weight sugars interact with starch and water, disrupting double-helix formation and reducing crystallinity, thereby inhibiting retrogradation (Su et al., 2024).

2.6. Mechanical Properties

The mechanical properties discussed in this study include maximum load, fracture strain, and elastic modulus. These parameters are commonly used to evaluate the strength, deformability, and stiffness of starch gels, providing valuable information on the structural changes that occur during storage.

2.6.1. Maximum Load

Maximum load, commonly referred to as hardness in texture analysis, is defined as the maximum force required to deform a gel during compression (Kwakye et al., 2024). It represents the resistance of the gel network against an externally applied force and is widely used as an indicator of gel firmness in starch-

based foods (C. Li, 2022). In starch gels, hardness reflects the strength of the three-dimensional network formed after gelatinization and is strongly influenced by the molecular interactions between amylose, amylopectin, and water. A higher maximum load indicates a stronger gel structure that requires greater force to deform, whereas a lower value corresponds to a softer and less rigid gel.

In starch-based products, hardness is one of the most important quality attributes because it directly influences texture, mouthfeel, and consumer acceptance. Products such as jelly, pudding, noodles, and starch-based desserts require an appropriate level of firmness to maintain their shape while remaining pleasant during consumption (C. Li, 2022). Excessive hardening during storage is generally considered undesirable because it reduces product softness and contributes to quality deterioration (Syahbanu et al., 2023). Therefore, hardness is frequently used to evaluate structural stability and storage performance of starch gels.

The increase in hardness during storage is primarily associated with starch retrogradation. After gelatinization, amylose molecules rapidly reassociate, followed by the slower recrystallization of amylopectin, resulting in the formation of more ordered crystalline regions (Chang et al., 2021). This structural reorganization strengthens intermolecular interactions within the gel network, producing a denser and firmer structure. Moisture migration further accelerates this process because water expelled from the polymer network allows starch chains to interact more closely (Lan et al., 2017). Consequently, starch gels generally exhibit progressively higher hardness as storage time increases. The extent of hardening is

also affected by starch composition, with starches containing higher amylose levels exhibiting greater retrogradation and consequently higher hardness (H. Zhang et al., 2023). Refrigerated storage at approximately 4°C has been reported to accelerate retrogradation compared with room temperature, resulting in a more pronounced increase in hardness (Gao et al., 2025).

The incorporation of sugars can significantly modify hardness development by altering starch-water interactions during gelatinization and storage. Sugars compete with starch for available water and interfere with starch chain reassociation, thereby reducing the rate of retrogradation (Z. Wang et al., 2024). Among the sugars studied, D-allulose has demonstrated a superior ability to suppress the hardening of amylopectin-rich starch gels compared with sucrose by preventing the tight realignment of starch chains and promoting a more flexible hydrogen-bonding network (Kwakye et al., 2024). Therefore, monitoring maximum load provides valuable information regarding the effectiveness of different sugars in maintaining the desirable texture of starch-based foods during refrigerated storage.

2.6.2. Fracture Strain

Fracture strain, also referred to as fracture deformation, represents the extent to which a material can deform before structural failure occurs. It is determined as the deformation distance at the fracture point, where the force–deformation curve shows a sudden decrease due to gel collapse (X. Wang et al., 2022). Unlike maximum load, fracture strain reflects the deformability and flexibility of the gel

network rather than its strength. Higher fracture strain indicates greater flexibility and elasticity, whereas lower values indicate a more brittle gel that fractures after limited deformation. Consequently, fracture strain is an important parameter for evaluating the structural integrity and textural quality of starch-based gels (L. Zhang et al., 2024).

The fracture behavior of starch gels is governed by the organization of the starch network following gelatinization. Swollen starch granules embedded within a continuous amylose matrix enable the gel to deform under stress. However, increasing starch concentration produces a denser polymer network that restricts deformation, resulting in lower fracture strain (Lan et al., 2017; Lyu et al., 2022). During refrigerated storage, progressive retrogradation further strengthens the network through the formation of crystalline junctions, increasing rigidity and consequently reducing gel deformability.

Sugars influence fracture strain by altering hydrogen-bond interactions within the starch network. Sucrose generally stabilizes the hydrated gel network but may promote structural heterogeneity during prolonged storage due to water redistribution, leading to increased brittleness (Allan & Mauer, 2022). In contrast, D-allulose forms relatively weaker hydrogen-bond interactions that help maintain a more flexible gel network and allow greater deformation before fracture, even after refrigerated storage (Kwakye et al., 2024). Therefore, fracture strain provides valuable insight into the ability of different sugars to preserve the flexibility and structural stability of starch gels during storage.

2.6.3. Elastic Modulus

Elastic modulus is a mechanical parameter that describes the stiffness of a gel network by measuring its resistance to elastic deformation (Ellis et al., 2019). In rheological analysis, it is represented by the storage modulus (G′), which reflects the energy stored within the material and the quantity and strength of internal starch–starch interactions (C. Li, 2024). Therefore, elastic modulus is widely used to evaluate the rigidity and mechanical stability of starch gels.

During cold storage, the elastic modulus generally increases as retrogradation promotes starch chain reassociation and reinforces the three-dimensional gel network (Rong et al., 2026). The formation of additional intermolecular junctions results in a more ordered and solid-like structure, indicating increased gel stiffness over time (X. Wang et al., 2022). Consequently, elastic modulus serves as a useful indicator of structural changes occurring during starch gel storage.

Sugars influence elastic modulus by modifying interactions between starch chains. According to the zipper model, sugars can form starch–sugar–starch hydrogen-bond bridges that stabilize the gel network and increase its stiffness(Ellis et al., 2019). Sucrose, which contains numerous equatorial hydroxyl groups, is particularly effective in creating these junction zones, thereby restricting starch chain mobility and increasing the elastic modulus (Chang et al., 2021). Therefore, this parameter is useful for evaluating the effects of different sugars on the rigidity and stability of starch gels during refrigerated storage.

CHAPTER III

MATERIALS AND METHODS

The study was conducted in November 2025 - February 2026 at the Food Protein Functionalities Laboratory, Faculty of Agriculture, Kagawa University, 2393 Ikenobe, Miki, Kita-Gun District, Kagawa 761-0701, Japan and at the Integrated Laboratory of Diponegoro University.

3.1. Research Materials

The experimental equipment consisted of creep meter (Model RE2-33005C, Yamaden, Japan), water bath (Model EW-100R, AS ONE Corporation, Japan), analytical balance (Model AUW220D, Shimadzu Corporation, Japan), beakers, graduated cylinders, and thermometer. The raw materials included sago flour (Healthy Choice), modified cassava flour (MOCAF; MOCAFINE), D-allulose, sucrose, and distilled water.

3.2. Research Methods

The research method consisted of experimental design, research procedures, parameter testing, and data analysis.

3.2.1. Experimental Design

This study was conducted using sago starch and MOCAF starch, which were processed into starch gels before treatment application. Each starch gel was assigned to one of three treatments: control (without sugar addition), sucrose

addition, and D-allulose addition. Sugar was added at a concentration of 10% of the starch weight used in the formulation. The prepared gels were subsequently stored for 3 days at 4 ± 0.5 °C. Mechanical properties were evaluated on Days 1, 2, and 3 throughout storage using a creep meter to determine the effects of starch type, sugar treatment, and storage duration on gel characteristics.

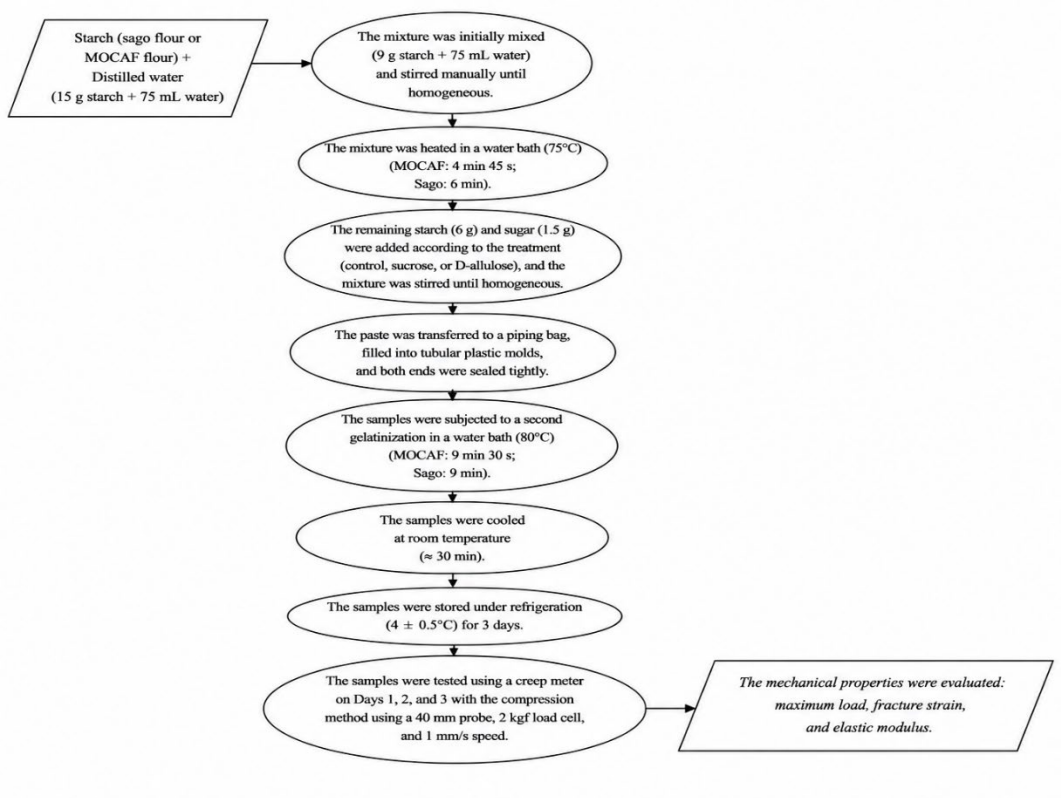
3.2.2. Research Procedure

Distilled water (75 mL) was measured using a graduated cylinder, while starch was weighed separately at 9 g and 6 g for each treatment. The initial 9 g portion of starch was dispersed in 75 mL of distilled water in a beaker and manually mixed using a stainless steel spatula until a uniform suspension was obtained. The suspension was subsequently heated in a water bath maintained at 75 °C while being continuously stirred to facilitate starch granule swelling and pasting through the combined effects of thermal energy and mechanical agitation. Heating time was 4 min 45 s for MOCAF starch, and 6 min for sago starch.

Following the pasting stage, the beaker was removed from the water bath and the remaining 6 g of starch was incorporated into the paste. Sucrose or D-allulose was then added according to the treatment at a level of 1.5 g, the sugar was added later to maximise the gelatinisation, due to the sugar restricting the granule swelling. The mixture was stirred until a homogeneous paste was achieved. The resulting paste was transferred into a piping bag, loaded into a syringe, and filled into tubular plastic molds. Both ends of the molds were tightly sealed to maintain

sample integrity, minimize moisture loss, prevent air incorporation, and ensure uniform sample geometry.

The water bath temperature was then adjusted to 80 °C, and the packaged samples were subjected to further gelatinization for 9 min 30 s in MOCAF starch gels and 9 min in sago starch gels. Upon completion of gelatinization, the samples were removed from the water bath and allowed to equilibrate at room temperature for approximately 30 min. The gels were subsequently stored for 3 days at 4 ± 0.5 °C, and each day (1st, 2nd, 3rd) was analysed using creep meter.



Ilustration 3. Flow Chart Starch Gel Process

3.2.3. Creep Meter Testing

The mechanical properties of the gels were tested using a creep meter with the compression method. Gel samples were placed on the testing platform and compressed using a cylindrical probe with a diameter of 40 mm. The test was conducted with a load cell capacity of 2 kgf. Samples were compressed at a speed of 1 mm/s. The force data generated during compression were recorded and analyzed using texture analysis software to determine mechanical parameters such as hardness and gel deformation characteristics.

3.2.4. Data Analysis

Mechanical characterization data were analyzed descriptively using Microsoft Excel 2021 (Microsoft Corp., Redmond, WA, USA). The average values of three independent replicates were plotted as line graphs to illustrate changes in mechanical properties during storage. Linear regression analysis was performed to evaluate the trends of mechanical properties over the storage period, and the corresponding regression equations and coefficients of determination (R^2) were reported.