AgriHealth
Journal of Agri-food, Nutrition and Public Health
ISSN 2722-0656 (Print) 2722-0648 (Online)

AgriHealth: Journal of Agri-food, Nutrition and Public Health. 6(2), 85-99, 2025
URL: https://jurnal.uns.ac.id/agrihealth/article/view/104436
DOI: http://dx.doi.org/10.20961/agrihealth.v6i2.104436

Development of Sorghum Flour-Based Edible Straws with Bovine Gelatin and Variations in Carboxymethyl Cellulose Concentration

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Received: June 19, 2025; **Accepted**: August 5, 2025

Abstract

Single-use plastic straw pollution is driving the need for environmentally friendly alternatives. This study aims to develop and characterize edible straws based on sorghum flour with the addition of bovine gelatin and analyze the effect of variations in Carboxymethyl Cellulose (CMC) concentration. A completely randomized design (CRD) was used in a non-factorial format with four levels of CMC concentration (0%, 1%, 3%, and 5%), each with three replications. The straws are made through mixing, semi-wet molding, and two-stage oven drying at 60 °C. The product's characteristics were tested, including water resistance, absorption, moisture content, organoleptic properties, and biodegradability. Data were analyzed using Analysis of Variance (ANOVA) and Duncan's Multiple Range Test (DMRT) to determine significant differences between treatments. The analysis showed that adding 3% CMC (C3) produced the optimal formulation, exhibiting the highest water resistance of 63.21 minutes in cold water, the lowest water absorption of 26.2%, and a final moisture content of 8.7%. This formulation also received the highest scores in organoleptic tests for color, aroma, taste, and texture. In contrast, 5% CMC caused the dough to become stiff. Straws show the best resistance to cold water temperatures, followed by normal temperatures. The key finding of this study is that all straw formulations can be fully decomposed (100%) in soil media within 15 days. It was concluded that this sorghum flour-based edible straw has excellent potential to replace conventional plastic straws as a functional and environmentally friendly alternative.

Keywords: biodegradability; Carboxymethyl Cellulose (CMC); eco-friendly; edible straw; sorghum

INTRODUCTION

Plastic pollution has become an urgent global issue, mainly due to the widespread use of single-use plastics. Plastic materials are highly resistant to natural degradation processes that take thousands of years to digest, causing long-term environmental accumulation and triggering extensive ecological damage to land and at sea (Embrandiri et al., 2021; Mandal et al., 2024). According to reports, about half of plastic waste comes from single-use items such as tableware, packaging, and plastic bags, which are poorly handled (Duru et al., 2019). Single-use plastic is made to be used only once and then discarded (Chen et al., 2021).

One of the apparent forms of single-use plastic waste is plastic straws, which occupy the fifth position in the most common types of waste in the oceans. In Indonesia alone, it is estimated that the use of plastic straws reaches more than 93 million sticks per day, which come from restaurants, packaged drinks, and various other consumer activities (Murniati, 2020). Different alternatives

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Cite this as: Silvia, D., Budi, A. A. S., Marshanti, N. S., & Arumdapta, D. S. (2025). Development of Sorghum Flour-Based Edible Straws with Bovine Gelatin and Variations in Carboxymethyl Cellulose Concentration. *AgriHealth: Journal of Agri-food, Nutrition and Public Health*, *6*(2), 85-99. doi: http://dx.doi.org/10.20961/agrihealth.v6i2.104436

to plastic straws exist, such as bamboo, stainless steel, glass, paper, and edible straws (Chitaka et al., 2020). However, each of these alternatives has its drawbacks. Bamboo straws are difficult to clean and prone to bacteria buildup; stainless steel straws generate waste that is difficult to recycle and is linked to sustainability issues in the nickel mining process (Chang and Tan, 2021); glass straws are prone to breakage and paper straws are easily weakened when in contact with beverages and often reduce the comfort of use due to inconsistent texture and taste (Agumba et al., 2023).

Among such alternatives, edible or biodegradable straws emerged as potential innovative solutions. Edible straws present a creative approach to waste reduction because they can be consumed directly or decompose naturally without polluting the environment, making them ideal for reducing the burden of plastic waste (Qiu et al., 2021). Edible straws are widely made from a mixture of polysaccharides, lipids, and proteins to create a waterproof structure and desirable mechanical properties. The challenge is to find a source of polysaccharides that is not only functional but also sustainable.

One of the most promising sources of polysaccharides for this purpose is sorghum flour. Sorghum flour is a promising natural ingredient in the development of edible straws. Sorghum is a grain crop that has exceptional resistance to diverse dry and soil conditions, making it a relevant candidate to support food security and land use (Sahara et al., 2023; Susilawati et al., 2023). Its cultivation requires less water and fewer agricultural inputs than other cereals such as maize, making it more eco-friendly and suitable for marginal lands. Sorghum also demonstrates high resilience to adverse climate conditions, including drought, high temperature, and water stress, positioning it as an essential defense against food shortages under climate change (Khalifa and Eltahir, 2023). Sorghum grain contains a high starch content of approximately 80.42%, composed primarily of amylopectin (57.03%) and amylose (25.58%), which are essential for the formation of flexible and biodegradable structures such as edible straws (Cahyadi et al., 2020; Yan et al., 2023). In addition to its availability and low production costs, sorghum flour has physical and chemical characteristics that favor the formation of flexible and sturdy structures, such as good gelatinization ability (Avif and Td, 2020). This makes it an ideal candidate for edible straw product formulations.

In developing polysaccharide-based straws, it is necessary to add binding and structuring agents such as Carboxymethyl Cellulose (CMC) and proteins such as gelatin. CMC is known to improve the viscosity and flexibility of the matrix, while gelatin from bovine sources supports the formation of a strong film structure (Tavares et al., 2019). CMC is a cellulose derivative obtained through the carboxymethylation of plant-based cellulose, allowing it to dissolve in water and form a viscous, stable solution, which functions effectively as a thickening and stabilizing agent (Rahman et al., 2021; Pirsa and Hafezi, 2023). Gelatin is a natural protein obtained through partial hydrolysis of collagen from animal connective tissues. This study uses bovine gelatin derived from non-edible parts such as skin, bones, and connective tissues, making its production more efficient and reducing waste in the livestock industry (Aksun Tümerkan, 2021). Using bovine-derived gelatin also allows for clear traceability, which is essential in halal assurance, mainly when sourced from certified slaughterhouses. Combining these materials will produce edible straw products with better water resistance and mechanical durability. Although many studies have explored ingredients from starch or protein, using CMC and gelatin combinations in sorghum flour-based straws is still limited (Rather et al., 2022).

Various studies have been conducted on developing edible straws as a solution to plastic waste, generally using a combination of starch and protein and functional additives. Research by Choeybundit et al. (2024) shows that hydrophobic coatings such as beeswax and shellac wax significantly improve the water resistance of soy protein isolate-based straws and cassava starch. The study of Anggraini et al. (2022) emphasized the importance of starch type and gelatin concentration in determining the physical properties of straws, such as moisture content and biodegradability. Another study by Samantha et al. (2023) shows the importance of mechanical reinforcement because straws made from rice bran and cassava starch have low tensile strength. The use of CMC as a booster has also been studied by Tavares et al. (2019) who proved that CMC increases the mechanical strength and hydrophobic properties of starch films. Meanwhile, Biduski et al. (2017) found that chemical modifications to sorghum starch improve the strength and stability of the film, making it a potential candidate for biodegradable products.

However, most studies still focus on extracted starch, not whole flour, and not many have explored the direct application of sorghum flour as a base for edible straws. This opens up further research opportunities to develop edible straws based on sorghum flour, gelatin, and CMC variations with a simple but effective formulation approach.

Developing edible straws based on sorghum flour, CMC, and gelatin represents a promising solution to single-use plastic waste and supports the sustainable utilization of local agricultural resources. This study aims to evaluate the effect of CMC concentration on the physical and functional properties of edible straws, including moisture content, water absorption, water resistance, and shelf life. Additionally, biodegradability and organoleptic assessments were conducted to determine the product's environmental performance and consumer acceptability. The results are expected to support the development of practical and eco-friendly straw alternatives in the future.

MATERIALS AND METHOD

Materials and tools

The main materials used in this study were sorghum flour (Timur Rasa), bovine gelatin (Hays), CMC (Koepoe-Koepoe), sorghum crystal sugar (Healthy Choice), distilled water (Water One), vanilla-flavored food flavoring (Zeelandia), and baking release agent (Zeelandia). All ingredients were commercially sourced and used without further modification. The equipment used included an analytical balance (Fujitsu), laboratory glassware, an oven for sample preparation (Samono), an oven for moisture analysis (Memmert), an aluminum rod 6061 (5 mm diameter), a stopwatch, a desiccator, and a digital thermometer.

Edible straw making

The manufacture of edible straws is done by mixing all ingredients according to the formulation listed in Table 1. Sorghum flour, bovine gelatin, sorghum crystal sugar, and food flavors are combined in a container. CMC is dissolved in hot distilled water (±85 °C) until it forms a gel, then added to the dry mixture and kneaded manually until a smooth and homogeneous dough is obtained. The dough is left to rest for 15 minutes, then shaped into a ball weighing ±15 g. The dough balls are wrapped in aluminum rods sprayed with baking release agent, flattened on an aluminum baking sheet until they form a cylinder with a consistent diameter and length of ±10 mm and ±13 cm, respectively, across all treatments.

The drying process is carried out in two stages. The first is baking at 60 °C for 120 minutes, while the dough is still attached to the aluminum rod. It is removed from the rod, and the second baking occurs at the same temperature and time. After that, the straws are stored in an airtight plastic container for retrogradation to improve structure and water resistance (Bangar et al., 2021).

Formulation of edible straw sorghum

This study applied a completely randomized design (CRD) in a two-factor factorial arrangement, consisting of four levels of CMC concentration (0%, 1%, 3%, and 5%) and four levels of storage duration (0, 5, 10, and 14 days). Each treatment combination was replicated three times. Data were analyzed using Analysis of

Table 1. Formulation of edible straw sorghum

Materials	Formulation			
	C0	C1	C3	C5
Sorghum flour (g)	10	10	10	10
CMC (%)	0	1	3	5
Bovine gelatin (%)	5	5	5	5
Sorghum sugar (%)	4	4	4	4
Food flavoring (%)	1	1	1	1
Aquadest (%)	6	6	6	6

Note: The percentages of CMC, bovine gelatin, sorghum sugar, food flavoring, and aquadest are expressed as weight percentage (%) relative to the weight of sorghum flour. For example, a 5% gelatin means 0.5 g of gelatin was added per 10 g of sorghum flour

Variance (ANOVA), and differences between means were evaluated using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

The formulation for making edible straws is presented in Table 1. Each formulation uses 10 g of sorghum flour as the main ingredient. CMC is added in concentrations of 0%, 1%, 3%, and 5% (w/w) to the weight of sorghum flour. Bovine gelatin was added consistently by 5% (w/w), while sorghum sugar and food flavors were added by 4% and 1% (w/w), respectively, all calculated based on the weight of the flour. For each formulation, 6 ml of aquadest is used.

Shelf life test

The shelf life test was carried out by storing the edible straws in 0.35-micron polyethylene (PE) primary packaging sealed with a heat sealer, followed by a secondary clip-lock plastic bag containing 4 g of silica gel, and then placed in tertiary cardboard packaging storage at room temperature (±25 °C) for 14 days. Observations were made on days 0, 5, 10, and 14, focusing on visual changes such as the appearance of mold, unpleasant odors, discoloration, or structural damage.

Moisture content test

The moisture testing begins with drying the cup by heating it in a 105 °C oven for 2 hours, then cooling it in a desiccant for 30 minutes before weighing. Then, a sample of ±3 g of edible straw is put into a crucible cup and heated again in the oven for 2 hours or until constant weight. Once finished, the sample is removed, cooled in a desiccant for 30 minutes, and weighed to record the final weight. The difference in weight before and after heating was used to determine the moisture content in the sample.

Water absorption test

Water absorption was tested by soaking a ±4 cm long dry straw at room temperature (±28 °C) for 30 minutes. Before and after immersion, the straws were weighed using an analytical scale to determine the increase in weight. The percentage (%) increase in weight is calculated as an indicator of water absorption.

Water resistance test

The water resistance test was carried out by soaking the straws using water at three different temperatures, namely low temperature (±5 °C), room temperature (±25 °C), and high temperature (±70 °C). Observation is made by recording the time until the straw leaks or begins to soften (Nahdi et al., 2022).

Biodegradability test

Biodegradability testing is a process to determine how quickly and completely a material can be broken down by microorganisms into simpler substances (Folino et al., 2023). The test was carried out by planting a sample 4 cm deep in a plastic container filled with soil. The straws were taken and re-weighed to find out the weight loss value and the degradation trend.

Organoleptic testing

Organoleptic testing assesses the sensory attributes of edible straws, including color, form, aroma, and texture. This test involved 15 trained panelists who evaluated the quality of the product using their senses (Ismanto, 2023). These trained panelists had prior experience and understanding of sensory evaluation procedures, allowing for more consistent and reliable assessments. Each panelist received coded samples presented randomly to minimize bias. The evaluation was conducted in a controlled room to ensure consistency in lighting and temperature. Panelists were asked to score each attribute using a hedonic scale of 5–4–3–2–1, corresponding to "very good", "good", "fair", "poor", and "very poor". The assessment focused on sensory quality (not functionality) and was designed to reflect panelists' perception of the product's appearance, smell, texture, and structural integrity.

Data analysis

The research data were analyzed using SPSS software to determine statistical significance. ANOVA is applied to all parameters to evaluate the influence of each treatment. If ANOVA indicates a significant difference, the analysis is followed by a post-hoc DMRT to identify which treatment groups are specifically different.

RESULTS AND DISCUSSION

Storage stability test

The 14-day shelf life observation showed that all treatments exhibited excellent visual stability throughout the storage period. Visually, no significant changes were observed in the straws' color, form, or surface integrity, and no mold growth or microbial growth was detected on any of the samples across all storage days.

Table 2 presents the visual appearance of the edible straws at days 0, 5, 10, and 14.

Although the differences between samples may appear subtle, a closer inspection reveals that straws with higher concentrations of CMC (3% and 5%) maintained better surface smoothness than those with 0% CMC, which showed slight surface dullness by day 14. Straws with 1% CMC displayed intermediate characteristics, retaining acceptable structural appearance but with minor

Table 2. Storage stability results in 14 days

Treatment	Storage days			
	Day 0	Day 5	Day 10	Day 14
C0				
C1				
C3				
C5				

wrinkling noticeable at later days. However, these changes remained minimal and did not indicate microbial spoilage or significant degradation.

These findings suggest that all treatments possess comparable short-term stability under ambient storage conditions (±25 °C) for up to 14 days. However, since the observation period was limited to 14 days, these results should be considered preliminary, and further long-term storage studies are recommended to determine the product's whole shelf life and potential degradation beyond this period. This test also analyzed samples on days 0, 5, 10, and 14 for moisture content, water absorption, water resistance, organoleptic properties, and biodegradability, as discussed in the following sections.

Moisture content test

Figure 1 shows that treatment factors and storage time significantly influence the moisture content in edible straws. ANOVA showed a significant primary effect of treatment ($F(3.32) = 11.172$, $p < 0.001$) and storage days ($F(3.32) = 6.787$, $p = 0.000$), as well as a significant interaction between treatment and day ($p = 0.03$), indicating that the effect of CMC concentration on moisture content was dependent on storage time. Duncan's further test showed that the highest moisture content was found in the control treatment (C0) at 9.51%, significantly different from C1 (7.27%) and C5 (7.98%), but not significantly different from C3 (8.71%). The most significant decrease in moisture content occurred in treatments with low CMC concentrations (0 to 1%).

During the 14 days of storage, the moisture content showed a significant downward trend from 9.31% (day 0) to 7.48% (day 14). This decrease is common in carbohydrate-based materials, as reported in previous studies on extruded flour of cereals and nuts, which showed a decline in moisture content and mass density depending on temperature and the type of packaging used (Forsido et al., 2021). The addition of CMC to the composition of sorghum-based edible straws significantly affected the moisture content, with a significant downward trend in moisture content at low concentrations of CMC (0 to 1%). This decrease supports the result that the starch structure of sorghum can lose water progressively during storage. With the moisture content of the product ranging from 7.27 to 9.51%, mold or mildew growth has been proven to be inhibited during 14 days of storage at room temperature. In general, mold growth on food products is influenced by several factors, including moisture content, water activity, storage temperature, and packaging conditions. Although this study did not include microbial count or water activity measurement, the absence of visible mold or mildew during 14 days of storage suggests that the moisture content (ranging from 7.27 to 9.51%) was sufficiently low to inhibit fungal growth under room temperature conditions (Lisa et al., 2015).

Water absorption test

Water absorption testing showed that treatment factors and storage time significantly affected the water absorption capacity (WAC) of edible straws. Bidirectional ANOVA results

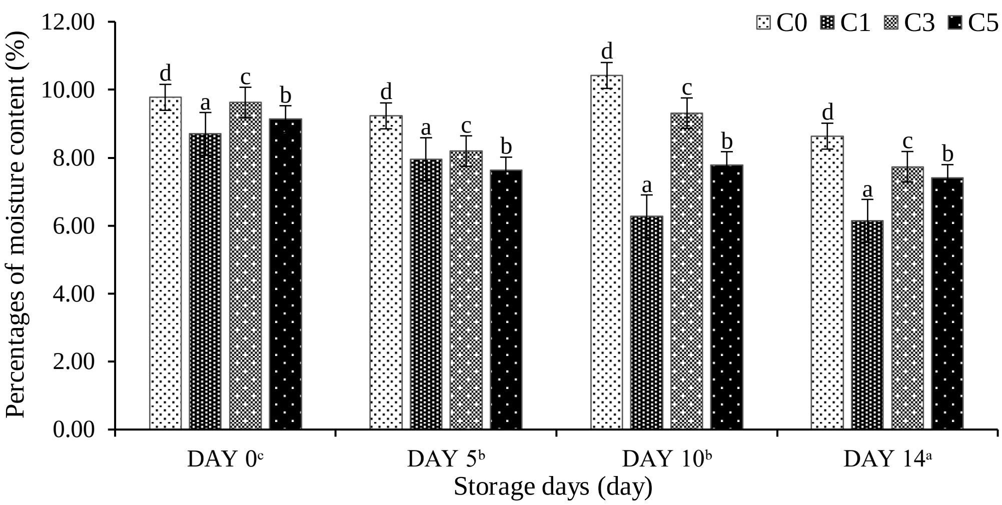

Figure 1. Effect of storage days and CMC addition on the moisture content test

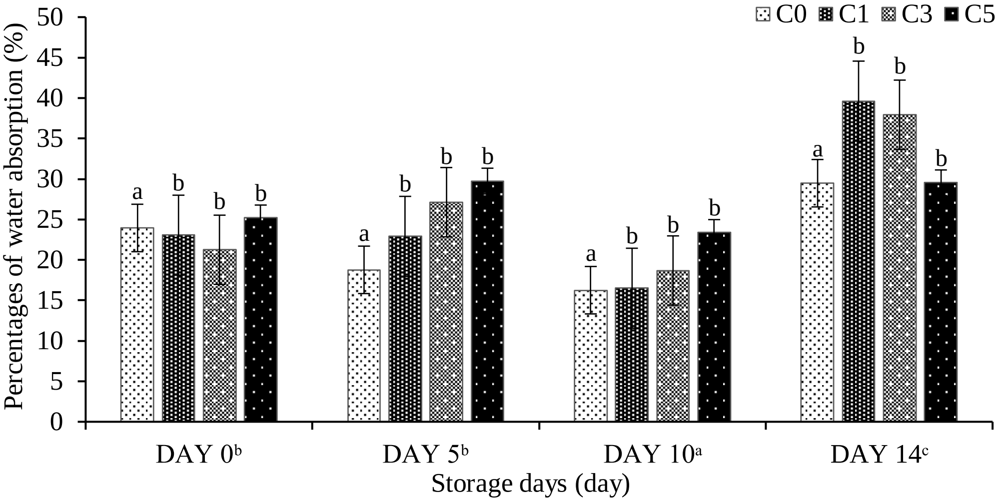

Figure 2. Effect of storage day and CMC addition on water absorption

showed significant main effects of treatment and storage days and significant interactions between the two (treatment × day, p < 0.001). This indicates that the impact of the treatment on water absorption depends on the day of observation. The graph shows the interaction pattern, where each treatment shows different WAC dynamics over time. The results of the water absorption test (Figure 2) showed that the most significant increase occurred on day 14, especially in the C1 (39.62%) and C3 (37.94%), while the lowest values were recorded on day 10 for the C0 (16.26%) and C1 (16.50%). These fluctuations underline that each formulation responds differently to the length of storage, which significantly affects the water absorption of edible straws.

The results of further tests showed that the C0 had the lowest absorption significantly (average of 22.11[a]), in contrast to the C1, C3, and C5 treatments, which had higher absorption but did not differ significantly from each other. This indicates that the addition of CMC generally increases water absorption. Significant effects were also observed regarding time, where day 14 showed the highest absorption (average 34.14[c]). The addition of CMC is known to increase water absorption due to its high hydrophilic properties, where CMC can absorb water strongly (strong water absorption) (Hashmi et al., 2020; Su et al., 2023). However, in the concentration range of 1 to 5%, the difference is not statistically significant, suggesting that the absorption capacity does not increase linearly as the CMC concentration rises, with a water absorption value of 22 to 27% showing quite good results compared to paper straws, namely 30% (Gutierrez et al., 2019).

Meanwhile, a significant increase in water absorption on day 14 is thought to be related to a fairly sharp decrease in water content, leading to empty spaces in the straw structure. This empty space increases the amorphous volume in starch granules, allowing greater interaction between starch hydrophilic groups and water molecules, thereby increasing WAC (Fairuza and Amertaningtyas, 2024; Zhang et al., 2024). These findings align with previous reports that low moisture content will increase the WAC of starch-based ingredients.

Water resistance test

The test results showed a significant three-way interaction between treatment, storage days, and temperature on the water resistance of edible straws ($F(18.96) = 5.476$, p < 0.001). This means that a combination of these three factors greatly influences the resistance of straws to water. Low temperatures generally provide the highest durability (Figure 3), especially in the C5 treatment on day 5 with a hold time of 61.67 minutes. Meanwhile, at normal temperatures (Figure 4), the best resistance was recorded in the C3 treatment on day 10 (51.67 minutes). In contrast, all treatments showed a drastic decrease in high temperature (Figure 5), with an average hold time of less than 25 minutes.

C3 treatment had the highest water resistance, significantly compared to other treatments, based on the results of the Duncan test (p < 0.05).

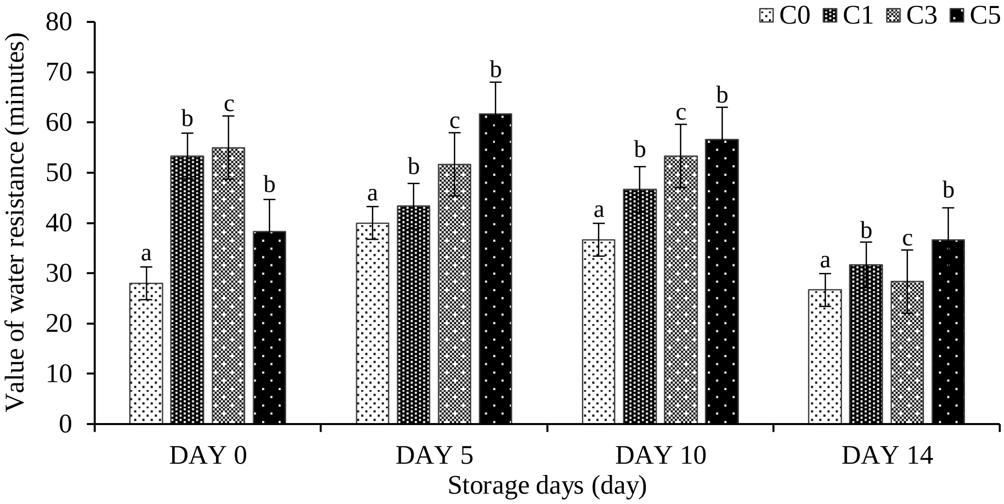

Figure 3. Water resistance at low temperatures of ±5 °C

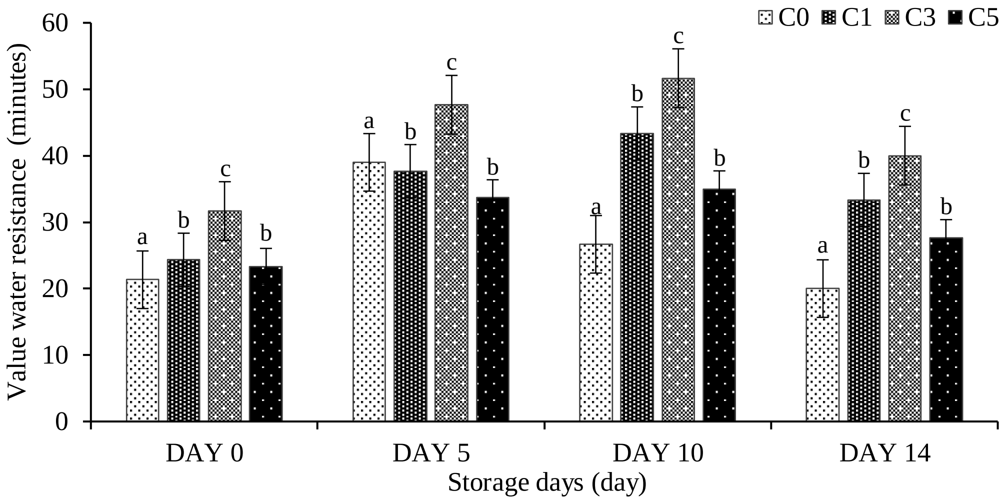

Figure 4. Water resistance at normal temperature ±25 °C

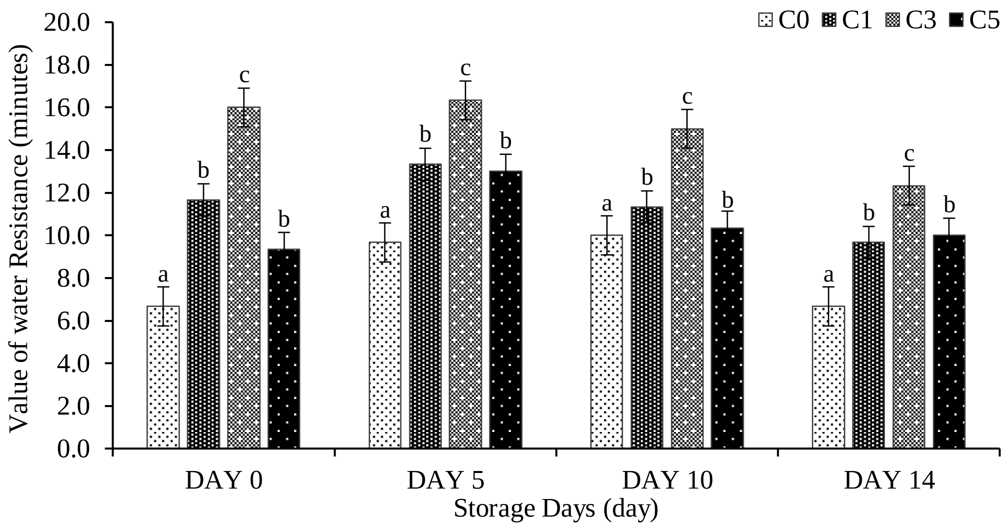

Figure 5. Water resistance at high temperatures of ±70 °C

Adding CMC up to a concentration of 3% effectively strengthens the structure of straws, allegedly due to the optimal interaction between CMC and gelatin. However, an addition of up to 5% decreases durability, which is likely caused by the water competition between CMC and gelatin, thus weakening the gel tissue.

The result of the test on the storage day factor in Table 3 showed that the 5th and 10th days were included in a group that was not significantly different. Still, the two significantly differed from the 14th day, with the lowest holding time (23.58 minutes). Day 0 was in between and not significantly different from the rest of the group. This indicates that storage up to day 10 can still maintain water resistance well, while day 14 shows a significant decrease, likely due to changes in internal structure during storage. Table 3 shows that the high temperature produces the lowest holding time (11.33 minutes), significantly different from normal temperature (33.52 minutes) and low temperature (43.00 minutes). This confirms that low temperatures maintain the stability of the gel structure, while high temperatures accelerate softening and physical damage to the straw.

The decrease in water resistance at high temperatures on day 14 was closely related to the increase in water absorption recorded on day 14 (Figure 2). This improvement indicates that the straw structure absorbs water more quickly, thus accelerating softening and deformation. The absorbed water breaks the hydrogen bonds between the polysaccharide chains and forms new bonds with the water molecules, creating a looser and more unstable gel tissue (Xu et al., 2020; Gong et al., 2024). Structures like these are more easily damaged when submerged and cannot maintain their functional shape as straws. Thus, it can be concluded that C3 treatment, with storage for 5 to 10 days and use in cold temperatures, is the optimal combination to maintain the durability of edible straws based on sorghum flour.

The longest water resistance is obtained in cold conditions, while the fastest is in high temperatures. Scientifically, this phenomenon is related to the solubility properties of solids in solvents. Rising temperatures tend to speed up the dissolution process because high temperatures can weaken the molecular bonds in solid materials, including the gel structure of edible straws, thereby accelerating the dissolution or degradation of the structure (Shoukat et al., 2020). The highest water resistance results at 62 minutes, which shows quite good results because the average time people spend in a cafe is less than 60 minutes (Ferreira et al., 2021).

Biodegradability test

All treatment groups (C0, C1, C3, and C5) were successfully degraded within 15 days (Figure 6). Initially, C5 underwent a more extended adaptation phase with slow degradation, while the rest showed gradual degradation. However, between the 10th and 12th days, C5 experienced the most drastic acceleration of degradation. On day 15, all samples achieved 100% degradation, proving that the tested formulation was biodegradable and fully degradable in the simulated environment.

Based on the test results, there was not enough statistical evidence to state that there was a difference in the biodegradability rate between treatments, both on day 10 ($p = 0.138$) and day 12 ($p = 0.061$). Although descriptively there may be a difference in average value, statistically the difference is not significant. Overall, the graph in Figure 6 indicates that the main difference between formulations is not in the final ability

Table 3. DMRT results for storage duration and water temperature

Factor	Level	N	Subset 1	Subset 2	Subset 3
Storage day	14	36	23.58		
	0	36		26.58	
	10	36			33.06
	5	36			33.92
	Sig.		1	1	0.333
Water temp.	High	48	11.33		
	Normal	48		33.52	
	Low	48			43.00
	Sig.		1	1	1

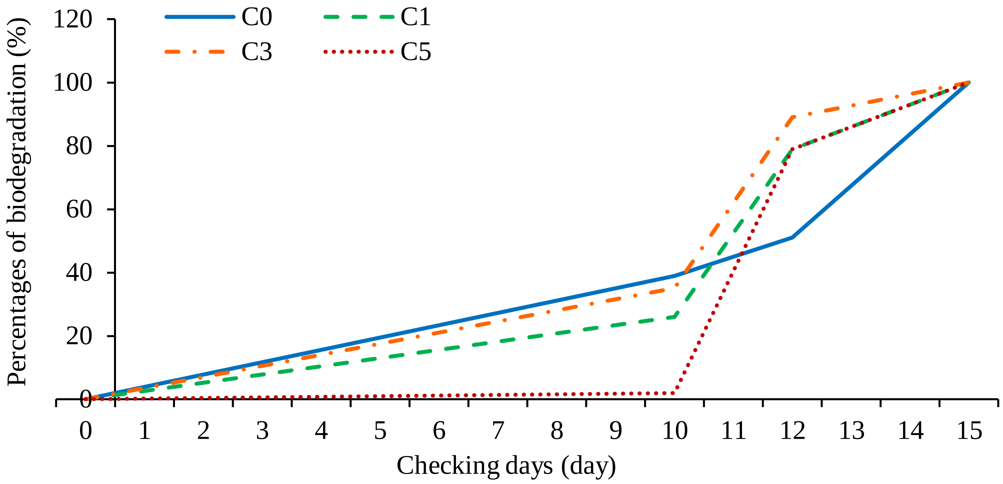

Figure 6. Percentages of biodegradability days from 0 to 15 days

a. b. c.

Figure 7. Biodegradability testing process: (a) Day 0, (b) Day 12, (c) Day 15

to decompose but in their kinetics or degradation patterns. The C5 formulation shows a classic pattern with a slow initial adaptation phase followed by rapid exponential degradation. On the other hand, the C0 formulation showed a more linear and stable degradation pattern from the beginning of the test.

The biodegradability of the edible straws was monitored over time, as illustrated in Figure 7, showing their physical appearance on days 0, 12, and 15. Edible straws based on sorghum flour with a main composition of ±95% are classified as naturally biodegradable. Although it does not meet the criteria of Indonesian National Standard 7818:2014, which requires ≥ 60% degradation within 7 days, this is understandable because the standard is intended for thin biofilms, not solid materials such as flour-based straws. Larger masses cause a slower degradation rate but achieve total degradation (100%) within 15 days. The predominance of natural biopolymer materials such as sorghum flour, accompanied by the addition of gelatin and CMC in small amounts (about 5 to 7%), proves that this formulation is biodegradable. This formulation is biodegradable, as seen in CMC, a natural polymer that is environmentally friendly and capable of decomposing perfectly in the soil (Mandal et al., 2024). In addition, gelatin, as a type of protein, is also known to be safe for ecosystems due to its ability to undergo biological degradation easily (Andreazza et al., 2023).

Organoleptic test

The results showed that the treatment (p = 0.000), day (p = 0.000), and their interaction (p = 0.000) had a significant effect on color. This interaction is evident at the peaks and lows during storage (Figure 8). The highest score was achieved on day 10 by the C0 (4.40^a) and C3 (4.27^b) treatments, which were significantly higher than C1 (3.67^a) and C5 (3.53^b). In contrast, the lowest scores were consistently seen in the C1 treatment, especially on day 0 (C1 = 2.40^a) compared to other treatments that started with a higher score (C0 = 3.40^b; C3 = 3.27^b; C5 = 3.53^b).

The test result showed a significant effect of treatment (p = 0.000), storage day (p = 0.003), and their interaction (p = 0.003) on the form of the edible straw. This indicates that both the formulation and storage duration, as well as their combination, influence the physical integrity of the straw. Among all treatments, C3 consistently exhibited the highest form scores (Figure 9), with a peak on day 5 (C3 = 4.93[c]), followed by C5 (4.80[b]), C0 (3.87[b]), and C1 (3.20[a]). The lowest values were consistently recorded in C1 on both days 5 and 0. This consistent pattern is visually supported by Figure 8, in which the C3 curve remains the highest throughout the storage period.

Aroma is significantly affected by the treatment (p = 0.000) and day (p = 0.000), but not by the interaction of the two (p = 0.099). Since the interactions are insignificant, the main effects can be interpreted directly, where day 5 is the best time for scent on all treatments (Figure 10). On the 5th day, the highest score is indicated by C0 (4.87[b]) and C1 (4.73[b]), followed by C3 (4.67[a]) and C5 (4.53[a]).

Texture is significantly affected by treatment (p = 0.000), day (p = 0.005), and their interaction (p = 0.000). These strong interactions show a very diverse pattern. The results of the organoleptic test score on texture (Figure 11), the highest value was obtained by C3 on day 14 (4.67[b]) and C0 on day 0 (4.53[b]). On the other hand, the lowest value was found in the C1 treatment, specifically on day 0 (C1 = 2.67[a]) and day 14 (C1 = 2.67[a]), where on those days other treatments showed a much higher score (day 0: C0 = 4.53[b], C3 = 3.73[b], C5 = 3.13[a]; day 14: C3 = 4.67[b], C5 = 4.07[a], C0 = 3.80[b]).

The results of the comprehensive ANOVA showed that treatment, storage days, and interactions both significantly influenced color, shape, and texture attributes, indicating that the effects of the treatment varied over time. Specifically, the C3 treatment stood out with the highest shape score on day 5 (4.93) and texture on

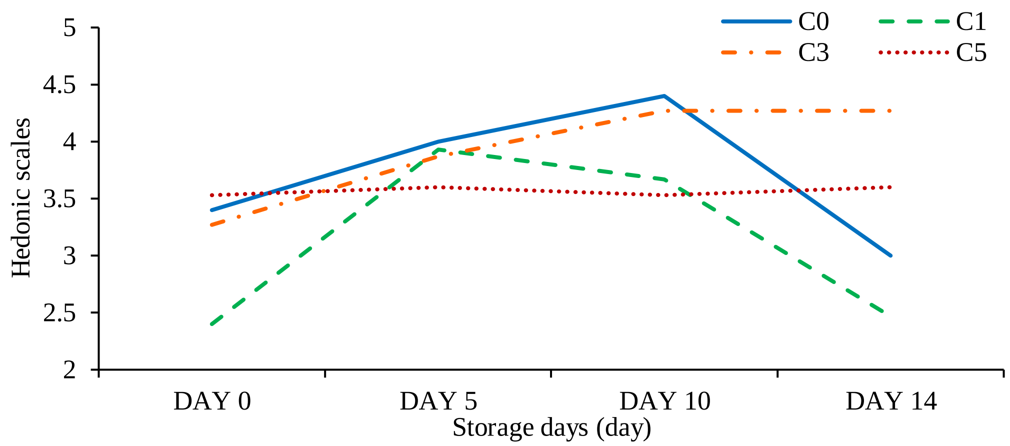

Figure 8. Effect of storage days and CMC addition on hedonic scores of color of sorghum-based edible straws

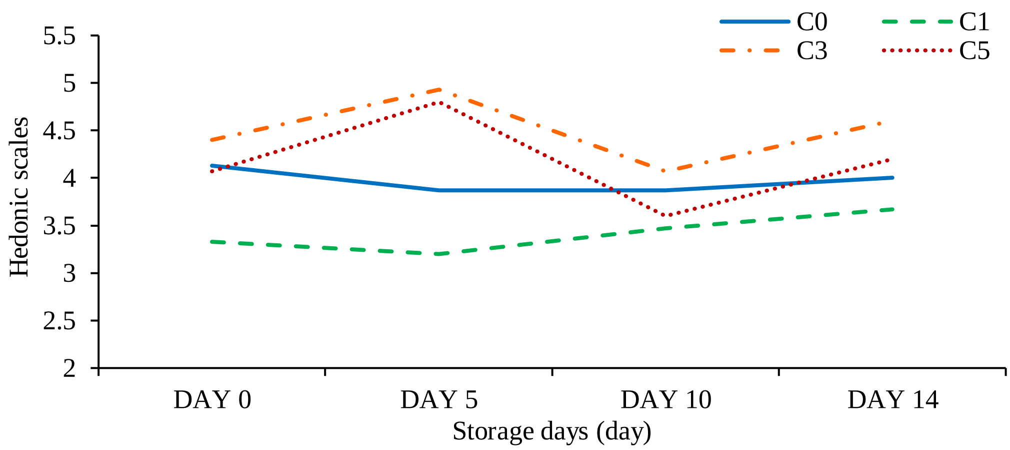

Figure 9. Effect of storage days and CMC addition on hedonic scores of the form of sorghum-based edible straws

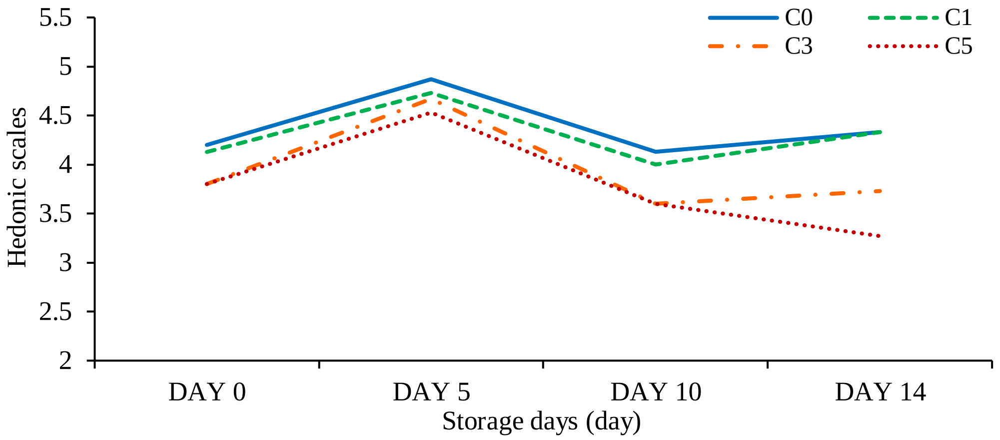

Figure 10. Effect of storage days and CMC addition on hedonic scores of aroma of sorghum-based edible straws

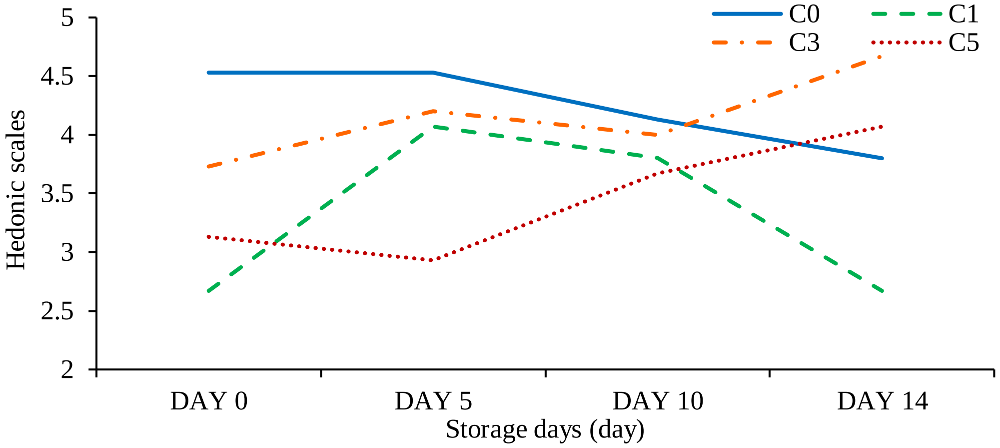

Figure 11. Effect of storage days and CMC addition on hedonic scores of texture of sorghum-based edible straws

day 14 (4.67), while C0 excelled in color on day 10 (4.40). For aromas, where interactions were insignificant, peak quality was generally achieved on day 5 across all treatments, led by C0 and C1. In contrast, the C1 treatment consistently showed the lowest performance in almost all attributes, especially on color and texture scores at the beginning and end of the storage period, making it the least effective treatment.

CONCLUSIONS

This study highlights the promise of sorghum flour combined with gelatin and optimal CMC levels in producing functional, biodegradable edible straws. The 3% CMC formulation (C3) offered the best balance of water resistance, structural integrity, and sensory quality, while higher concentrations compromised flexibility. Although C3 retained shape over 14 days, moisture content and absorption changes suggest that storage and packaging require optimization. The straws decomposed fully within 15 days in soil, underscoring their sustainability. Utilizing local sorghum provides environmental and socioeconomic benefits. Future work should address microbiological safety, enhance hot water resistance, extend shelf life, and explore industrial-scale manufacturing. Trials on industrial-scale production and mechanical strength testing are also essential to accelerate commercialization.

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