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FULL PAPER

Synergistic effect of kappa-carrageenan and konjac flour in enhancing physicochemical and organoleptic properties of wheat-based edible straw

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Abstract

The development of edible straws is an affordable solution to reduce the use of plastic tableware as well as a promising innovation to promote an eco-friendly lifestyle. This study was aimed at producing wheat-based edible straw made by combining high-protein wheat flour with kappa-carrageenan, konjac flour, salt and water. All ingredients were introduced to mixing, kneading, resting, dough rolling, dough flattening, molding, and baking. The effect of six different proportions of kappa-carrageenan and konjac flour (100:0, 80:20, 60:40, 40:60, 20:80, 0:100) on the physicochemical and organoleptic properties of wheat-based edible straw was evaluated. The water content of edible straws from all treatments ranged from 7.07-8.12%. Among the six treatments, the maximum synergy of kappa-carrageenan and konjac flour in producing high gel strength and desired edible straw characteristics was obtained from the proportion of 60:40 with the produced edible straw possessed the lowest water activity (*aw*), percentage of water absorption at tested temperatures (0-5, 25-30, and 65-70°C), turbidity, and fracturability. The results of the organoleptic evaluation showed that the panelists slightly liked and could accept the aroma and color of wheat-based edible straw made with the proportion of kappa-carrageenan and konjac flour 60:40.

1. Introduction

The convenience and low price of plastic have brought communities to utilize plastic products in daily lives. However, the poor waste management and lack of public awareness leads to the global crisis of plastic waste. Plastic is a polymer that takes many years to decompose and will persist in environment for hundreds of years. The accumulation of plastic waste has eventually posed detrimental effects to many aspects, including agricultural land, marine environment, animal, and human health (Kedzierski *et al*., 2020).

The food and beverage sector accounts for a large proportion of plastic waste from disposable tableware, such as food wrappers, food and beverage containers, cutlery, and straw (Hussain *et al*., 2020; Ncube *et al*., 2021). The reduction of aforementioned plastic usage can be endeavored through modifying the materials used to make the tableware (Gautam and Caetano, 2017). In this study, edible straw was developed as one affordable solution to plastic waste issue in the beverage product sector. Edible straw is made from food ingredients that undergo cooking process, thus making it ready to be used and safe to be consumed. Moreover, unlike the plastic straw, edible straw is environment-friendly, completely biodegradable, and able to decompose (Natarajan *et al*., 2019).

Edible straw can be made based on flour or starch. In order to be optimally used, edible straw should have certain characteristics such as fracture resistance, insoluble in various beverage temperatures, and absence of distinctive aroma and taste. In order to meet those criteria, high-protein wheat flour with the protein content of 12-13% was chosen as the basic ingredient to produce the edible straw (Hackenberg *et al*., 2018). Besides having plain flavor and aroma, high-protein wheat flour contains complex protein called gluten. Each component of gluten, namely glutenin and gliadin, offers different unique characteristics that can provide a rigid structure to the edible straw (Li *et al*., 2021). The continuous network of glutenin proteins through the polymerization disulfide bonds is responsible for creating an elastic and strong dough, whereas gliadin provides plasticity toward the glutenin polymeric network and preserves the whole

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protein structure (Han *et al*., 2020). Glutenin and gliadin, after being added with water and introduced to kneading process, form a strong three-dimensional gluten matrix that generate a strong, stretchy dough and allows the dough to be shaped as desired (Cappelli *et al*., 2020).

In addition to high-protein wheat flour, a mixture of hydrocolloid consisting of kappa-carrageenan and konjac was also incorporated in the present edible straw formulation. Hydrocolloids possess an important role as gelling agents targeted to strengthen the structure and lower the water absorption rate of the wheat-based edible straw (Rohmah *et al*., 2019). The gelation of kappa-carrageenan is initiated by heating which changes the random coil structure into a helix structure. A decrease in temperature favors the helices to associate with each other to form a hard, brittle thermo-irreversible gel. Compared to other types of carrageenan, kappa-carrageenan is less soluble in water due to the presence of hydrophobic 3,6-anhydrous-D-galactose group with lesser amount of hydrophilic sulfate ester group (Geonzon *et al*., 2019). On the other hand, konjac is a high molecular weight, water-soluble polysaccharide containing glucomannan with a very high water absorptivity (up to 50 times its weight in water). Glucomannan comprises of the main chain of β-1,4-linkages that connect D-glucose and D-mannose backbones, and slightly branched through β-1, 6-glucosyl units. Gels of konjac can be both thermo-reversible and thermo-irreversible (Ji *et al.*, 2017).

The combined use of kappa-carrageenan and konjac flour was based on the ability of konjac flour to enhance the properties of kappa-carrageenan gel. The synergistic interaction between these hydrocolloids will produce a stronger, more elastic and stable gel due to the association and lining up of the mannan molecules into the junction zones of helices (Chen *et al*., 2019). However, previous studies also indicated that the improvement of gel quality was influenced by the optimal proportion of kappa-carrageenan and konjac. Tunieva *et al*. (2021) found out the ratio of 1:1 was the optimal ratio of kappa-carrageenan and konjac gum to generate strong and plastic gels. The same conclusion was also reported by Kaya *et al*. (2015). Another study by Wei, Wang and He (2012) reported the strongest gels was produced from combining kappa-carrageenan and konjac gum with the ratio of 5.5:4.5. Therefore, the aim of this study was to investigate the effect of various proportions of kappa-carrageenan and konjac flour in producing wheat-based edible straw with ideal physicochemical characteristics. Furthermore, the selected treatment was proceeded to the organoleptic test to evaluate consumer acceptance of the wheat-based edible straw.

2. Materials and methods

2.1 Materials

Commercial high-protein wheat flour containing 13% protein, table salt, and drinking water were purchased from local market in Surabaya, Indonesia. A technical grade of Kappa-carrageenan and konjac flour were obtained from PT. Algalindo Perdana, Indonesia.

2.2 Preparation of wheat-based edible straw

Wheat-based edible straws were prepared by mixing high-protein wheat flour (150 g), kappa-carrageenan (0-7.5 g), konjac flour (0-7.5 g), and table salt (1.5 g) with water (100 mL). The amount of kappa-carrageenan and konjac flour was adjusted in such a way that their proportion came to 100:0 (P1), 80:20 (P2), 60:40 (P3), 40:60 (P4), 20:80 (P5), and 0:100 (P6) with the total amount of 7.5 g. The mixture was thoroughly kneaded until uniform and rested for 30 mins. The dough was rolled using rolling pin and further flattened using dough flattener to a thickness of ± 0.08 cm. The thin dough was cut into a rectangular shape (15 cm × 2 cm) and molded around the surface of stainless-steel straw covered with baking paper to form a cylindrical shape. The dough was baked at 100°C for 1 hr, cooled at room temperature for 1 hr, and packed inside a PP plastic added with pouched silica gel.

2.3 Moisture content and water activity

Moisture content of wheat-based edible straw was measured thermogravimetrically according to Association of Official Analytical Chemists method (AOAC International, 2005). Water activity was measured using *aw* meter (Rotronic, Switzerland).

2.4 Texture analysis

The fracturability evaluation of wheat-based edible straw was performed using a texture analyzer (TA-XT2 Texture Analyzer, Stable Micro System, England) according to Carsanba and Schleining (2018) with some modification. The sample was laid on two supports and subjected to a shear test using a 3-point bending rig until the sample snapped into two. The pre-test speed was 3 mm/s, test speed was 3 mm/s, and post-test speed was 10 mm/s. The fracturability was determined based on the maximum peak force (N) which indicated the cutting force of wheat-based edible straw.

2.5 Water absorption test

Water absorption test was performed according to the method proposed by Harouna *et al*. (2019) with some modification. Similar weight of the samples from all treatments were prepared. The prepared samples were immediately immersed in cool (5-10°C), room (25-

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30°C), and warm (65-70°C) water. The samples were taken out from the water, drained, weighed, and re-immersed in the water every 5 mins for 20 mins. The percentage of water absorptivity was calculated using the equation below:

$$\text{Water absorptivity (\%)} = \frac{weight\ \ after\ immersion\ -\ weight\ \ before\ immersion}{weight\ \ before\ immersion} \times 100\%$$

2.6 Solubility evaluation using turbidity test

The level of turbidity represents the amount of wheat -based edible straw's solids leached out into the beverage product. The turbidity test was performed by immersing the wheat-based edible straws into warm water (65-70°C) for 10 mins. The turbidity of the water was analyzed using a turbidimeter (Velp Scientifica, Italy) and the results were expressed in Nephelometic Turbidity Units (NTU).

2.7 Organoleptic evaluation

Wheat-based edible straw that possessed the lowest Aw, water absorptivity, turbidity, and the highest fracture resistance was proceeded to the organoleptic evaluation. The evaluation was conducted by 100 untrained panelists with the parameters of wheat-based edible straw tested were color and aroma. The samples were evaluated using a five-point hedonic test with line scales (1 = strongly dislike, 5 = strongly like).

2.8 Statistical analysis

All the analyses were done four times and the results were expressed as mean ± standard deviation (SD). A one way analysis of variance (ANOVA) was performed to analyze differences between treatments. If significant difference was found, the treatments were compared by using Duncan's Multiple Range Test ($p \leq 0.05$).

3. Results and discussion

The proportions of kappa-carrageenan and konjac flour used in this study were 100:0; 80:20; 60:40; 40:60; 20:80; and 0:100. Parameters evaluated were edible straw's moisture content, water activity (*aw*), texture, water absorption capacity, turbidity, and organoleptic (color and aroma).

3.1 Moisture content and water activity

The determination of moisture content was performed to investigate the amount of free or weakly bound water contained in edible straws made from wheat flour formulated with different proportions of kappa-carrageenan and konjac flour. Information on the moisture content is closely related to the shelf life of the edible straw since the moisture content available in food can be used by microorganisms such as bacteria, molds, and yeasts to grow, thus can affect the quality of food product (Gichau *et al.*, 2020). In addition, other quality parameters such as texture, fracture strength, water absorption, and turbidity effect are also influenced by moisture content. The effect of the proportion of kappa-carrageenan and konjac flour on the moisture content of wheat-based edible straws can be seen in Figure 1. The results showed that the moisture content ranged from 7.07-8.12%. Based on the statistical analysis, there was a significant difference in the proportion of kappa-carrageenan and konjac flour on the moisture content of wheat-based edible straws. As presented in Figure 1, the lowest moisture content of edible straws was observed in the proportions of kappa-carrageenan and konjac flour of 100:0 (P1) and 0:100 (P6), while the highest moisture content was found in the proportion of 60: 40 (P3). The decrease of kappa-carrageenan resulted in the rise of the moisture content of edible straw until the proportion of 60:40. However, further decrease of kappa-carrageenan proportion led to an increase or a decrease of moisture content. Both hydrocolloids can create a network and bind with water due to the hydroxyl group (Chen *et al.*, 2019). Thus for 100% of kappa-carrageenan and 100% of konjac flour added in the formulation of edible straw did not show a significant difference in the moisture content. Although hydrocolloids have a high water-binding capacity, the water trapped is mainly in a weakly bound state and can still be released during the heating process (Zhou *et al.*, 2021).

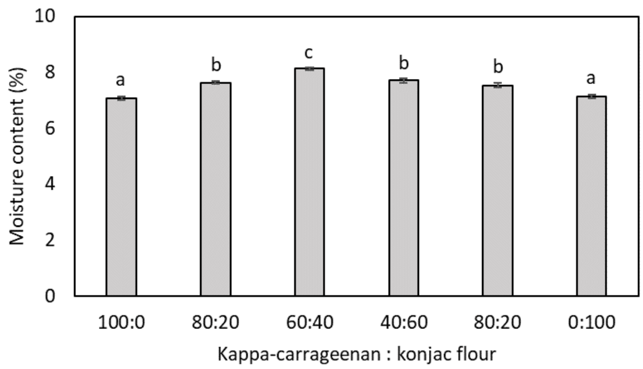

Figure 1. Moisture content of wheat-based edible straw. Bars with different notations are statistically significantly different at α = 5%.

Figure 1 also reveals that edible straw with a combination of kappa-carrageenan and konjac flour had a higher moisture content than an edible straw with only kappa-carrageenan (P1) or konjac flour (P6) due to the synergistic effects between kappa-carrageenan and konjac flour in creating the gel network with a better water binding capacity than kappa-carrageenan or konjac flour individually (Yang *et al.*, 2019; Wu *et al.*, 2021). The glucomannan compounds present in konjac flour will enter the junction zone of the kappa-carrageenan gel structure and are responsible for producing stronger bonds with water (Wang *et al.*, 2021). This bond plays a

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significant role in retaining the water inside the edible straw structure and avoiding evaporation in the processing stage of heating; thus, the moisture content is higher. However, further increase of konjac flour proportions which were 40:60 (P4) and 20:80 (P5) resulted in a decrease of moisture content due to the saturated condition of the double helix structure kappa-carrageenan, which then could not accommodate the increase of konjac flour. As a result, the konjac flour will form a gel outside the double helix structure of kappa-carrageenan. In this condition, the dough could absorb the water. However, the water will be easily removed during the baking process of edible straws.

The proportion of kappa-carrageenan and konjac flour that produced the highest moisture content of edible straw was 60:40 (P3), which could be due to the optimum synergy between kappa-carrageenan and the konjac flour at P3 proportion. The complex was formed when the konjac gel entered the double helix structure of kappa-carrageenan gel together with the gluten formation, making the complex produced the maximum water holding capacity. The edible straw dough could bind the water, thus minimizing its release during the baking step (Farbo *et al.*, 2020). The results of this study are in line with the previous research (Rhim and Wang, 2013), which stated that the use of a combination of kappa-carrageenan and konjac flour resulted in a higher moisture content of hydrogel film due to the water barrier properties. The common characteristic of edible straw is having a low moisture content concerning the shelf-life capability. Overall, the moisture content of flour-based edible straws in this study was higher than that of sorghum flour-based edible plates (2.57%) (Sood and Deppshikha, 2018).

Water activity (*aw*) is one parameter that determines the shelf life of food products (Moschopoulou *et al.*, 2019). *Aw* is defined as the amount of free or unattached water contained in food and food products. Free water can be used for microbial growth. Therefore, the higher the free water available, the higher susceptibility of food to microbial contamination and leads to the shortening of the shelf life (Barbosa-Cánovas *et al.*, 2020).

Different proportions of kappa-carrageenan and konjac flour affected the *aw* of wheat-based edible straws (α = 5%) (Figure 2). The *aw* of edible straw was ranging from 0.360-0.464. As described in Figure 2, the highest *aw* value was found in the kappa-carrageenan and konjac flour proportions of 100:0 (P1) and 0:100 (P6) with no significant difference between the treatments. Meanwhile, the lowest *aw* value was observed in the proportion of 60:40 (P3). Thus, the combination of kappa-carrageenan and konjac flour could yield a lower *aw* value than the single-use of kappa-carrageenan or konjac flour. This result agrees with the previous work conducted (Chen *et al.*, 2021), which suggested that the synergy between kappa-carrageenan and konjac glucomannan is responsible for lowering the *aw* of the product. The optimum proportion in lowering *aw* of edible straw was 60:40 (P3), which is believed to be the interaction effect between kappa-carrageenan and konjac flour. Konjac gel formed during dough formation will penetrate the junction zone of the kappa-carrageenan gel structure, creating a solid network in entrapping available water leads to the lower *aw* value.

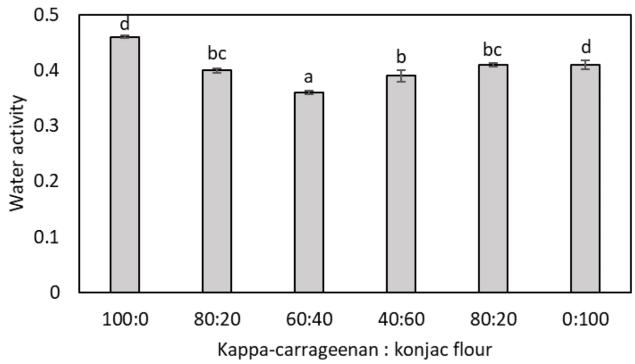

Figure 2. Water activity of wheat-based edible straw. Bars with different notations are statistically significantly different at α = 5%.

On the other hand, the increase of konjac flour proportion could increase the *aw* of edible straw because the double helix structure of kappa-carrageenan could not accommodate the excess of konjac gel. Thus, the network created failed to entrap the free water and increase the *aw* (Dai *et al.*, 2018). Additionally, the konjac flour used to produce edible straw also contains starch, protein, and fiber, which in their native form having a water-binding capacity (Huang *et al.*, 2016). Nevertheless, in the edible straw network, such components in higher concentrations will inhibit the creation of glucomannan and kappa-carrageenan networks and are responsible for increasing *aw* value. The highest water content in P3 shows the lowest aw due to the increase water absorption because of the starch, protein, and fiber. Thus, more water is available but the entrapment from the gel network tightly bound the water and resulted in the lowest aw value.

3.2 Texture

In this research, the examined texture parameter was fracturability. This test could describe the strength or sturdiness of edible straws during transportation, distribution, and utilization. Fracturability is the maximum force in Newtons (N) required to break the product. Therefore, the higher fracturability value indicates the strength of edible straw.

The effect of the proportion of kappa-carrageenan

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and konjac flour on the fracturability of wheat-based edible is presented in Figure 3. The fracturability ranged from 14.995-29.954 N, and a significant difference was observed with the different proportions of kappa-carrageenan and konjac flour (α = 5%). The lowest fracturability value was found when 100% of the konjac flour or kappa-carrageenan were used in the formulation of edible straw because the kappa-carrageenan and konjac flour could not optimally contribute to the formation of the firm structure of edible straw constructed by wheat and other ingredients. In contrast, the highest fracturability value was found in the 60:40 (P3) proportion of kappa-carrageenan and konjac flour. The interaction between kappa-carrageenan and konjac flour contributes to the gel strength of edible straw. The synergistic effect of the solid but brittle structure of kappa-carrageenan together with elastic and robust structure of konjac flour produces a strong structure of edible straw with a higher fracturability value (Hou *et al.*, 2022). The brittleness of kappa-carrageenan will be reduced by the presence of konjac flour in the edible straw dough due to the elasticity properties of konjac and the ability of konjac to preserve water in their structure (Yang *et al.*, 2017).

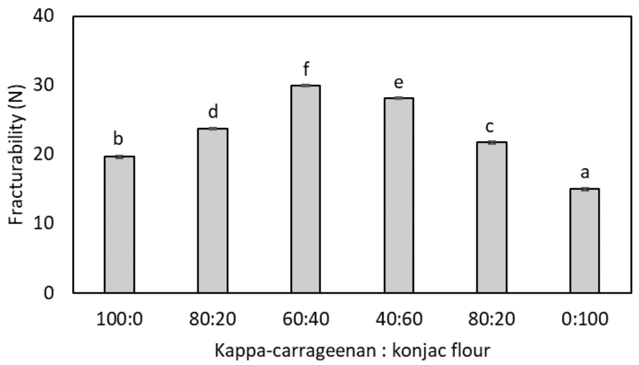

Figure 3. Fracturability of wheat-based edible straw. Bars with different notations are statistically significantly different at α = 5%.

A solid and elastic gel from the combination of kappa-carrageenan and konjac flour will produce a firm edible straw. Glucomannan compounds in konjac flour are believed to be absorbed in the junction zone of the kappa-carrageenan double helix structure, thereby reducing the brittleness of the kappa-carrageenan gel and producing a solid and elastic gel. In addition, the combination of kappa-carrageenan and konjac flour increases the fracturability, while on the contrary, the proportions of 40:60 (P4) and 20:80 (P5) decrease the fracturability of edible straw. The increase of fracturability in the proportions of 80:20 (P2) and 60:40 (P3) was due to konjac flour's role in reducing gel fragility of kappa-carrageenan the edible straw became sturdy and elastic. On the other hand, the proportions of 40:60 (P4) and 20:80 (P5) was responsible for the decrease of fracturability due to the higher proportion of konjac flour that inhibits the gluten formation as the primary structure builder of edible straw (Akesowan, 2015). The results in this study support the previous research conducted by Akesowan and Choonhahirun (2014) on the effect of kappa-carrageenan and konjac flour used in the production of orange juice jelly, which reported that the gel strength of the combination of kappa-carrageenan and konjac flour yielded a strong jelly structure.

3.3 Water absorption

Water absorption capacity is the ability of edible straw to absorb water. The higher water absorption capacity leads to a higher amount of water absorbed resulted in the decrease of the hardness of the edible straw. Edible straw made of flour is susceptible to water absorption when soaked in water or liquid. The addition of kappa-carrageenan and konjac is intended to decrease edible straw's water absorption capacity, thus retaining the structure and inhibiting the soggy structure changes of edible straw. This research used three different temperatures to describe a cold, a room temperature, and a warm drink. The water absorption capacity of edible straw is presented in Figures 4a, 4b, 4c.

It can be seen that longer soaking time and higher water temperature were responsible for the increase of the water absorption capacity. When the edible straw is soaked, the water penetrates the structure of the straw, resulting in increased water absorption. Moreover, the higher the water temperature, the mechanical movement of water will assist the water molecules to penetrate the straw structure (Zhu *et al.*, 2019). Meanwhile, the water absorption was increased significantly in the 5^{th} minute due to a large amount of water transferred to the immersed dried straw. Immersing the edible straw for more than five minutes affects the water absorption capacity because some amount of water is already absorbed by the straw. The existence of water in the structure inhibits the water absorption rate due to the water equilibrium stage (Li *et al.*, 2019). A study by Yu *et al*. (2017) on the effect of soaking brown rice reported that the water temperature and cooking time affected the water absorption capacity. The higher temperature of the water provided mechanical movement, thus exuviating the rice's surface and creating access for water to penetrate the structure of the brown rice. Meanwhile, time also contributed to the water absorption due to the breakdown of rice structure and immersing time until the equilibrium condition.

From Figures 4a, 4b, and 4c, it can be seen that the individual treatment of kappa-carrageenan and konjac flour resulted in the highest water absorption capacity.

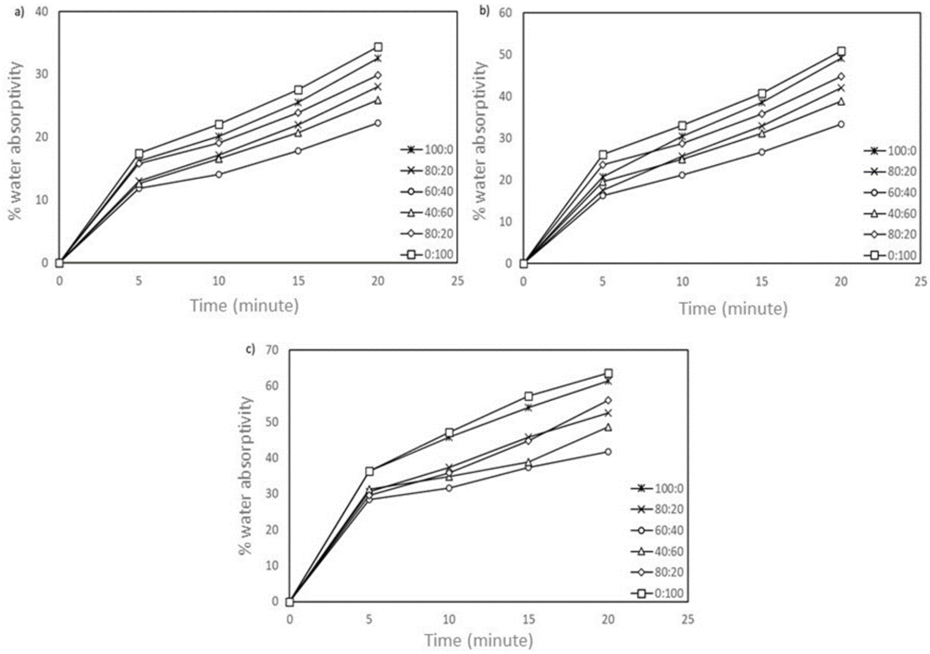

Figure 4. Water absorptivity of wheat-based edible straw at (a) 5-10°C, (b) 25-30°C, and (c) 65-70°C

Starch, protein, and fiber in the ingredients are responsible for the absorption of water. Moreover, kappa -carrageenan and konjac are also a strong water absorber for gel forming when individually exist in the formulation. On the other hand, the synergistic effect of mixed kappa-carrageenan and konjac flour successfully decreased the water absorption capacity because of the ability of konjac gel to form a strong network with kappa -carrageenan, thus inhibits the water penetration to the edible straw structure. Moreover, the gluten formed in the edible straw dough also plays a significant role in supporting the network initiated by kappa-carrageenan and konjac flour, thus forming a stronger network bond.

3.4 Turbidity

The turbidity test was intended to determine the ability of edible straw to maintain its structure and examine the solubility of edible straw. In addition, the result of the turbidity test will provide an overview of whether the structure of edible straw is rupture and creating turbidity in the beverage system and affecting the taste of the beverage consumed (Yildiz and Karhan, 2021). The turbidity occurs because of the release of solids from the edible straw structure into the beverage product. The results of turbidity test presented in Figure 5 shows the turbidity unit values ranged from 77.1-100.1 NTU, with the highest turbidity unit in edible straw with 100% kappa carrageenan. On the other hand, the combination of kappa-carrageenan and konjac flour at 60:40 resulted in the lowest turbidity unit, which means that the hydrocolloids could prevent solids from the edible straw structure their capacity to create a matrix network and bond with other ingredients. Moreover, other interactions contribute to a firm structure: water-starch, water-hydrocolloid, water-protein, protein-hydrocolloid, and protein-starch bindings (Yemenicioğlu *et al.*, 2020) absorption capacity is the ability of edible straw to absorb water. The higher water absorption capacity leads to a higher amount of water absorbed resulted in the decrease of the hardness of the edible straw. Edible straw made of flour is susceptible to water absorption when soaked in water or liquid.

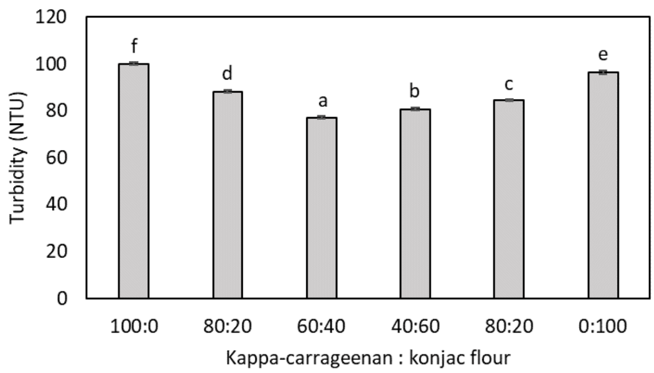

Figure 5. Turbidity test of wheat-based edible straw. Bars that do not share similar letters denote statistical significance at α = 5%.

3.5 Organoleptic evaluation

Organoleptic properties of color and flavor were examined with the preference test using a hedonic scale. The preference test was conducted for the edible straw made with the kappa-carrageenan and konjac flour proportion of 60:40 that exhibited the best objective parameters, including moisture content, fracturability, water absorption capacity, and turbidity value. A number of 100 untrained panelists contributed to the preference test. The result in Figure 6 revealed that the score for edible straw's color was 3.52 (slightly like), which means

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that the panelists still could accept the edible straw. The limit of acceptance is score of 3. The dark brownish color of edible straw is influenced by the baked wheat flour color and Maillard reaction. Meanwhile, the average score of the flavor preference test was 3.47 (slightly like). The lower organoleptic score for flavor could be due to the baked flour aroma that dominated the edible straw.

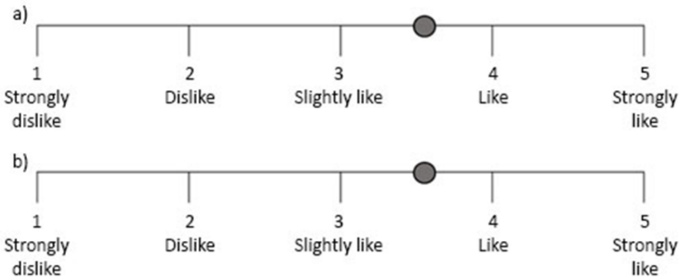

Figure 6. The organoleptic test results for (a) color and (b) aroma of wheat-based edible straw

4. Conclusion

Edible straw as one form of cutlery can be developed using wheat flour and a combination of kappa-carrageenan and konjac flour to improve its physicochemical and organoleptic properties. The synergistic effect of kappa-carrageenan and konjac flour decreased edible straw's moisture content and water activity, thus prolonging its shelf life. Meanwhile, the increased fracturability of edible straw was increased, which means that the structure became firmer and elastic with the addition of kappa-carrageenan and konjac flour. Furthermore, the combination of kappa-carrageenan and konjac flour decreases the water absorption capacity of edible straw, which enables it to be used to consume beverages and stand firm for a more extended time. The turbidity test of the beverage after immersion of edible straw shows that the combination of kappa-carrageenan and konjac flour decreases the turbidity of the beverage. The edible straw made with the kappa-carrageenan and konjac flour proportion of 60:40 exhibit the best objective parameters Moreover, the organoleptic test revealed that the best treatment of edible straw has a score of like slightly in the preference test.

Conflict of interest

The authors declare no conflict of interest.

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