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Production and application of octenyl succinic-modified starch as fat replacer: a review of established and recent research

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Abstract

Along with the rapid development of the trend in the health sector, various studies have been conducted to find alternative healthier foods, one of which is reducing fat consumption. Currently, many researchers focus on one of modified starches that can be utilized as a fat replacer is starch modified with OSA (octenyl succinic anhydride). In the last decade, there have been quite a lot of publications related to OSA starch, further the number is still increasing. This review discusses the synthesis method of OSA starch and its optimization, functional characteristics, and its application to be a fat replacer in many kinds of products daily consumed. Various pre-treatment methods could be applied to create OSA starch which has higher degree of substitution values. The presence of conjugate bonds with the OSA group in starch polymers could produce very amphiphilic starch characteristic so as to have an emulsifying function. Emulsions shaped from OSA starch were utilized as fat replacers in foods with high level of fat content. Partial OSA starch substitution was successfully utilized as a fat replacer for several types of food products with similar sensory attributes or even slightly better than the native product. The resulting product could be defined as a healthier choice because it had relatively lower fat and calorie content. Even so, adjustments through further study are still needed so that the food produced is able to have a higher level of sensory acceptance relative to native food without fat substitution.

Keywords:
Fat replacer, Octenyl succinic anhydride, OSA starch, Starch properties

Introduction

Consumption of excess saturated fat in daily food diets is such of the most imperious predisposing factors that may lead to an increased risk of the development of some illnesses including cancer, hypertension, cardiovascular disease, obesity and also type 2 diabetes (Krauss et al., 2001; Mozaffarian et al., 2016; Afshin et al., 2019). The World Health Organization (WHO) informed that in 2015 around 39% of the world inhabitants experienced overweight and 13% experienced obesity. The burden of medical care costs related to cases of obesity in developed countries continues to increase, for example in the USA of $3429/person/year (Biener et al., 2017), in Australia of $2501/person/year (Lee et al., 2018); in Japan of $2450/person/year (Kusunoki-Tsuji et al., 2018). Based on various negative impacts caused, various world health agencies such as WHO seriously encourage the reduction of fat, cholesterol and saturated fatty acids consumption. It is recommended to consume no more than 30% of the sum of calories from fat and no more than 10% of total energy intake from saturated fat (Sacks et al., 2017; Nettleton et al., 2018). The American Heart Association recommends individuals who have high level of LDL (low-density lipoprotein) cholesterol to restrict the consumption of saturated fats to not exceed 7% of total calories (Krauss et al., 2000). Research has shown that reducing fat consumption could lower the risk of cardiovascular disease by 10%, especially for people who were overweight, it could reduce the risk by up to 20% (Cengiz and Gokoglu, 2007). For example, replacing the intake of saturated fats using polyunsaturated vegetable oil could lower the pibility of experiencing cardiovascular disease by 30%, almost the same as reduction achieved through treatment using statins (Sacks et al., 2017).

Along with the increasing importance and awareness of the public to reduce fat consumption, low-fat products continue to be developed since the consumers believe that those products are healthier. Modern lifestyles and increasingly busy consumer schedules require the availability of low-fat fast food. The popularity of low-fat foods in recent years has increased along with the growth of low-calorie food trends. Thus, this provides an opportunity for the development of fat replacer products that retain the sensory characteristic of fat excluding its negative effects.

Innovation in providing low-fat foods is not as easy as one might imagine, given the role of fat which is crucial in the formation of distinctive sensory characters so that its role is difficult to replace. As a food component, fat provides specific appearance, taste, aroma, texture, and mouthfeel characteristics. Fat also has an effect on the intensity and balance of other available flavors. This event occurs due to the fat ability to release flavor slowly (slow release) (Lucca and Tepper, 1994). Fat also contributes to the main physiological benefits of increasing satiety during eating (Sipahioglu et al., 1999). The creation of foods with low level of fat labeled with disposed high-fat foods creates huge challenges that must be faced by food producers (Zoulias et al., 2002). Modification to such products by reducing the fat content directly is obviously not effective, because there is a decrease in quality that can inhibit food acceptance. Nowadays, fat replacer is rather frequently seen as the most potent solution for this problem (Thaiudom and Khantarat, 2011). Substitutes are expected to replace for the loss of properties associated with fat and increase the acceptance of low fat diets (Warshaw et al., 1996). Besides imitating the function of fat, one shoul need fat replacer to show low energy density with the result of reduced sum of calorie content int the product. This has encouraged many food experts to develop fat replacers, both carbohydrate and protein based.

Recently, one of the ingredients that has been intensively studied as an alternative to using fat is octenyl succinic anhydride (OSA) starch. Starch is one example of natural polysaccharide with a function as a food reserve in plants. Starch is also an example of biomaterials available abundantly on earth. Esterification of starch using octenyl succinic anhydride covers hydroxyl group substitution with a hydrophobic group so as to give the starch several properties of amphiphilic and interfacial. The result of this modification is called OSA starch. Based on the potential use of OSA starch as a substitute for food fat, this review summarizes the methods of OSA starch synthesis, functional characterization, and several breakthrough applications regarding specific utilization of OSA starch in the food sector as a fat replacer.

OSA Starch

Synthesis and optimization

OSA starch is a chemically modified starch using a starch esterification process by involving octenyl succinic anhydride compound. With non-full substitution of the hydroxyl group with the hydrophobic group, OSA starch has amphiphilic and interfacial properties, which are soluble in water and some organic solvents. OSA starch is often utilized as an emulsifier and encapsulant. There are several factors that affect physicochemical characteristics of OSA starch namley nature of the starch utilized as raw material, the processing surroindings during modification, the degree of derivatization, and newly

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established groups distribution. Therefore, synthesize by using various different properties can be applied to OSA starches in each application.

Starch esterification in order to establish hydrophobic groups to create derivatives possesing emulsifying properties was first patented by Caldwell and Wurzburg (1953). They explain the reaction of polysaccharides (for example starch) that are esterified using anhydride-substituted cyclic dicarboxylic acid. Three options are available: (1) the wet method which consists of a slurry reaction with a pH from 7 to 11; (2) a dry method which consists of a waterless reaction of acid and starch that has been processed before with a base solution; and (3) organic suspension method using organic liquid to replace water as a dispersing medium.

At present, the most commonly used method of OSA starch synthesis is by suspending granular starch into water and putting OSA droplets (Altuna et al., 2018). The solution is then stirred and the pH is maintained at 8 by using NaOH. The reaction is performed between 25−35°C and continues until it reaches a stable pH. After the reaction is complete, the mixture is filtered and the results are rinsed using acetone and water or ethanol, and at last they are dried and ground. Starch modification level is measured using the degree of substitution (DS), which is the mean substituents per anhydroglucose unit. DS is calculated using titration or ^1H NMR. The maximum amount of OSA as recommended by the FDA as food is 3% (w/w), the theoretical value of DS is 0.0231 assuming that whole OSA reacts together with the starch.

Optimization of OSA starch synthesis was first carried out by Jeon et al. (1999), who investigated the influence of various parameters on succinylation. Afterwards there were many researchers who also studied the optimization of the synthesis. In general, optimization aims to find the best reaction efficiency (RE) to get OSA starch with high DS. The pre-treatment of starch granules is usually performed with the aim of reducing the crystallinity of the granules or destroying the surface of the granules so as to facilitate OSA penetration into the starch granules, or by reducing the size of the OSA droplets so that the cavitation effect is obtained. And this may increase the surface area so that the esterification reaction runs more optimally and evenly. Pre-treatments include mechanical treatment (Zhang et al., 2010; Wang et al., 2015), ultrasonic waves treatment (Chen et al., 2014), hydrothermal treatment (Chen et al., 2014; Jiranuntakul et al., 2014), acid hydrolysis treatment (Sweedman et al., 2014), and enzymatic treatment (Bai and Shi, 2011). Details of the pre-treatment methods can be seen in Table 1 below. Combination of several pre-treatment methods might be able to further increase the RE and DS of OSA starch. Unfortunately, there is currently no combined pre-treatment method (more than one pre-treatment) studied.

Table 1 Pre-treatment methods for optimizing the esterification reaction in OSA starch synthesis

Pre-treatment Method	Key findings	Reference
Mechanical treatment	By raising the mechanical activation time to 10 hours using ball milling, starch crystallinity showed a progressive and significant decrease, and there were an increase in DS and RE values simultaneously (57% in DS and RE increased from 54.22 to 85.16%).	Zhang et al. (2010)
	In situ mechanical treatment could increase DS by 11% and RE increased (78.45 to be 86.86%) during high speed cutting treatment (10000 rpm).	Wang et al. (2015)
Ultrasonic treatment	The most optimal treatment with ultrasonic waves was obtained at the electrical power of 600 W. OSA starch was produced with a DS value of 15% more than the control, and RE increased from 75.78 to 87.63%.	Chen et al. (2014)
Hydrothermal	Pre-treatment showed starch contact with water at different temperatures (48-62°C) with stirring for 3 hours. OSA starch was best produced when the pre-treatment temperature was 60°C (increase in DS value by 16%, and RE increased from 72.20 to 81.76%).	Chen et al. (2014)
	Starch with octenyl succinylation heat-moisture treatment (25% water content, 100°C) for 1-5 hours showed higher DS and RE than the untreated control. In the treatment for 5 hours, DS increased by 18% and RE increased from 66.49 to 78.09%.	Jiranuntakul et al. (2014)
Acid hydrolysis	Acid hydrolysis pre-treatment using HCl could increase DS in starch with high amylose content. Conversely, DS tended to decrease in waxy and normal starch.	Sweedman et al. (2014)
Enzymatic	Pre-treatment towards waxy corn flour granules with α-amylase and glucoamylase could increase DS by 9%.	Bai and Shi (2011)

Pasting and emulsifying characteristics of OSA starch

Pasting properties

Pasting properties are assessed during heating and cooling cycles to starch suspension performed in water along with regular stirring. Furthermore, viscosity is assessed as a force resistant to stirring. The parameters resulted drom in this measurement are pasting temperature (PT) and peak viscosity (PV). PT is known as the temperature when maximum viscosity is reached, that is, the temperature at which the starch granules reach the maximum developmental paste suspension until further break. At this temperature starch will reach maximum viscosity. PV is the viscosity of the paste produced during heating. The increase in paste viscosity due to the water which was natively outside the granules and move unhamperedly before the suspension is heated now is already inside the starch grains and cannot move freely anymore. At this point the starch granule is fully expanded, when the swelling of the granule is higher, the maximum viscosity will be higher too. Maximum viscosity also illustrates the fragility of the expanding starch granules, i.e. from the time they first expand until the granules break during mechanical continuous stirring by the Brabender/Rapid Visco Analyzer (Baah, 2009; Li et al., 2014).

In line with the results DSC previously described, many researchers observed a decrease in PT in OSA starch generally obtained by conventional methods. PV values tended to increase in OSA starch compared to unmodified native starches, regardless of plant sources (Bao et al., 2003; Han and BeMiller, 2007; Chung et al., 2010; Carlos-Amaya et al., 2011). This is related to the involvement of OS groups which change the structure of starch sequence and break the hydrogen bonds to obtain swelling and higher penetration at lower temperatures (Bello-Flores et al., 2014).

However, the mentioned trends can change, depending on the type of pre-treatment provided before the modification process. Wang et al. (2015) reported that there was a reduction in PV and PT in OSA starch provided with mechanical pre-treatment with high shear force compared to the control. PT reduction is caused by particle damage from shear force so that starch is more easily destroyed by heat while PV reduction is caused by a more homogeneous distribution of OSA groups. PT reduction results in lower temperature to cook food ingredients to achieve a certain viscosity thereby saving costs and energy. Conversely, Chen et al. (2014) in their study found conflicting result. By applying hydrothermal pre-treatment, the PT and PV values of OSA starch were found to be significantly increased compared to the control. This change occurred due to the starch granules were strengthened by heating, resulting in a rearrangement of the starch composition. This can be useful in applications in foods that require high viscosity such as jam.

OSA starch forms a stable emulsion system

Emulsion is a heterogeneous system consisting of two phases of liquid that are not mixed but such liquid is well dispersed in another liquid as granules (droplet/globula) with a diameter usually more than 0.01 µm or between 0.01-50 µm. The granular phase is called the dispersed phase or the internal phase or also called the discontinuous phase, while the liquid phase with the dispersed granules is called the dispersing phase or the external or continuous phase. Food emulsions exist in the form of water in oil (W/O) (i.e butter and margarine) or oil in water (O/W) (i.e milk, cream, mayonnaise) which are stabilized by amphiphilic compounds. Without the presence of amphiphilic compounds coalescence and flocculation may take place in emulsions, most of which during storage, resulting in phase separation which lead the system to loose its functionality and acceptance (Agama-Acevedo and Bello-Perez, 2017, Mi et al., 2016). To be a good emulsifying agent, a material must own an interfacial property. Therefore, the more dominant hydrophilic starch must also have a hydrophobic group that allows the starch to stick and spread on the surface so as to stabilize the emulsion.

OSA starch is known as a stable emulsifier since the starch hydroxyl group is replaced by OSA in water dispersions which produce very amphiphilic and active surface properties (Zhao et al., 2018). OSA starch has a high affinity power to reduce surface tension in water, which is an important factor for making stable emulsions. More stable droplet conditions can avoid flocculation between oil particles (Tesch et al., 2017). In a 10% solid and water temperature of 25°C, the surface tension of the OSA Starch is 30-50% which is lower than Arabic gum. Emulsions formed by OSA starch have a uniform size and good stability in storage (Sweedman et al., 2014). Song et al. (2014) found that as the microstructure of an oil in water (O/W) emulsion stabilized with OSA starch (from rice) was viewed using an optical microscope, there was an accumulation of emulsion particles formed on the water-oil surface, forming a layer that solid at a concentration of 5%. This property is caused by the steric hindrance of the octenyl succinate chain which brings the OSA starch molecule to the surface of the water. The amylopectin chain also prevents emulsions from flocculation and coalescence. This specific property is an advantage of OSA starch compared to other emulsifiers such as egg yolks that contain high cholesterol levels and the potential to experience microbiological damage (Chivero et al., 2016).

The determinants of OSA emulsifying capacity are molecular weight, strength of the hydrophilic portion of the polymer chain and the amount of amylopectin with a low hydrodynamic radius. Various sizes and also shapes of corn-based emulsifiers (dissolved starches, granules, and precipitated starches) may have an impact on the size and stability of the resulting emulsion droplets. The best size and best shape for successive emulsifiers are starch deposits, dissolved starches and starch granules. Corn starch deposits are more potential as emulsifiers than granules and dissolved starches due to a low decrease in droplet size and they are stable to coalescence and creaming (Sari et al., 2019). Matos et al. (2016) also reported that the dissolved starch form was more active on the surface than the granular form. Furthermore, Tesch et al. (2002) stated that despite a higher viscosity during the continuous phase, the pH value and the valence ion had no effect on the stability of OSA starch. OSA starch is known to be better to be used than whey protein because it was not influenced by pH and valence ions. OSA starch can be used at low pH near the iso-electric point without concern of clotting. The use of OSA starch as an emulsifier can also have the advantage of not affecting the color since OSA starch is transparent. This transparent nature is obtained from the OSA substitution in the hydroxyl group thereby slowing the formation of starch paste and retrogradation and increasing the brightness of the final product (Hu et al., 2016).

Application of OSA starch as a fat replacer

There should be special attention to observe the role of OSA starch as a fat replacer to work well in complex food matrix systems. Reducing fat in food product formulations can cause some significant changes, due to reduced interaction of fat with fat, fat with protein and fat with carbohydrates (Peng and Yao, 2017). In solid foods such as cheese and sausages, fat replacers must be capable of maintaining the plastic properties possessed by the product. Usually low-fat solid products have a high level of hardness and poor melting power (Kahyaoglu et al., 2005). Whereas in thick liquid food products such as chocolate milk, yogurt, and ice cream, fat replacer must be able to maintain consistency and viscosity of the product. Usually low viscous liquid food products have poor viscosity (Sakiyan et al., 2004). In addition to functional properties related to food processing, changes in sensory characteristics also need attention. Reserachers should observe whether the addition of fat replacer may cause a decrease in sensory character of the product or not. Differentiation/discrimination tests in sensory analysis such as duo-trio, triangle test, and pair wise comparison are very agrreable for the creation of new products namely low fat products (Grujić et al., 2014). Fat replacer usage is expected to at least be able to maintain sensory character.

OSA starch is a cheap, fat-free ingredient that has excellent paste and emulsion formation properties. Many producers use emulsions from OSA starch as fat replacers in foods with high fat content. In addition, OSA starch also has a functional health characteristic that is slow digestibility so that it is very potential to be developed in the formulation of a variety of functional food products (Het et al., 2008; Peng et al., 2015). Many recent studies have shown that OSA starch is used in food formulations as a fat repalcer or emulsifier. A summary of the applications and results of their use in food can be seen in Table 2.

Minas fresh cheese

Fresh Minas cheese is popular and mass produced in Brazil. It has a soft texture with a fresh, salty and sour aroma and white color is the result of fermentation of the *Lactococcus lactis* subsp. *cremoris* and *Lactococcus lactis* subsp. *lactis.* A study on the application of the use of OSA starch from waxy corn as a fat replacer in Minas fresh cheese was conducted by

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Diamantino et al. (2014), who formulated the use of OSA starch of 0.5kg/100L. In general, the results of the study produced higher protein and water content while lower fat content relative to the control. Increased cross-linking between protein chains formed a compact matrix so that it produced harder cheese with a more chewy texture, while higher water content values indicated that mimetic fat increased the product water content as the value of water holding capacity (WHC) increased. This condition provided an advantage in preventing whey exudation, thereby facilitating the growth of bacteria that produce lactic acid. However there was a negative effect namely accelerated syneresis rate of the product. Organoleptically, the use of OSA starch in cheese making produced quite good characteristics on the third day of observation with a higher value of compactness, elasticity and plasticity compared to cheese without OSA starch. Furthermore, the use of OSA starch had an effect on the moisture content, protein content and ash content and the level of cheese hardness and increased the WHC value of low-fat cheese, although there was no significant effect on the microstructure or its proteolysis, texture parameters and yield values of low-fat cheese products. Thus, OSA starch has the potential to ameliorate the overall quality of fresh low fat Minas cheese products.

Salad dressing

A study on the application of the use of OSA starch as a fat substitute in salad dressing was conducted by Klaochanpong et al. (2017). Waxy potato starch and waxy rice in the form of granules and debranched (hydrolyzed with the pullulanase enzyme) were modified by adding OSA at a concentration of 3% as a fat replacer to make salad dressing. The concentration value of 3% OSA is the maximum level of use determined by many countries (Bhosale and Singhal, 2007; Liu et al., 2008). As a result, substitution with OSA debranched starch was evidenced to be more effective than OSA granule starch which experienced a significant decrease in quality at 3 days of storage. In fact, the substitution of 95% soybean oil using OSA debranched starch was able to provide results that had the similar quality to commercial salad dressings and couldn last up to 90 days of storage. In addition, when the egg yolks used in the recipe were reduced to half the initial amount, there was no significant change in texture. No phase separation was found in the product. The calorific value was also shown to be lower, with 50% and 10% of the basic recipe and a commercial product, respectively. However, there was a slight drawback where the color obtained was slightly paler (less glossy).

Mayonnaise

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Mayonnaise is a kind of semi-solid emulsion generated by mixing vegetable oils, acidulants (vinegar), and egg yolks (Nikzade et al., 2012). Although it contains 70-80% fat, mayonnaise is generally an oil in water (O/W) emulsion. Egg yolks in mayonnaise can form flocculation and emulsion to generate a texture as desired (Depree and Savage, 2001). However, one main problem with these ingredients is the relatively unwanted cholesterol content by many people. One effort to substitute egg yolk content with OSA starch modified from waxy corn starch was carried out by Chivero et al. (2016). The study was conducted by substituting egg yolks using 10g OSA starch to make 70 g of mayonnaise samples (40, 50, and 60 g of vegetable oil). As a result, OSA starch could form a stable emulsion from egg yolk substitution at a fat content of 60% in mayonnaise. The emulsion exhibited pseudoplastic behavior similar to mayonnaise in general. Meanwhile, mayonnaise with fat content of above 60% cannot be fully emulsified. In addition, it was also found that a higher fat content and increased amount of starch granule sediments could increase long-term stability. However, the study did not discuss organoleptic changes related to the mayonnaise.

Furthermore, a study conducted by Ghazaei et al. (2015) regarding egg yolk substitution with OSA modified potato starch for mayonnaise products with low cholesterol found that the best ratio between OSA starch and egg yolk based on the results of rheological test was 75:25. In addition, there was no significant difference based on sensory evaluation in mayonnaise samples (75% and 100% substitution) after one month related to the taste, odor, color, appearance and texture of the control (without substitution). The study findings also showed that partial substitution of egg yolks with OSA starch could reduce cholesterol levels in mayonnaise by 84% to 97%. Slightly different from the findings of the study conducted by Ghazei et al. (2015), Ali and co-authors succeeded in making a low-fat mayonnaise formulation by substituting 75% of oil through the addition of 20% OSA starch. Organoleptic result obtained better product which has similar texture to commercial mayonnaise products. Thus, the study finding indicates that there was great potential in making mayonnaise product with low cholesterol levels without experiencing significant changes in sensory or rheological aspects.

A study on OSA modified starch from various starch sources applied in the substitution of 75% fat compared to full fat mayonnaise was carried out by Bajaj et al. (2019) who observed rheological results and sensory properties. Various sources of starch included flour, corn, lilies, potatoes, sweet potatoes, rice and kidney beans. OSA modified starch was obtained by dissolving 20% starch suspension with various pH variations in 3% NaOH and 3% HCl. Sensory results showed that the panelists were not affected by OSA modified starch substitution with the order of consistency favored by the panelists: OSA modification rice-corn-potato-kidney beans starches, while the viscosity value was higher compared to without OSA modified starch. In addition, the effect of substituting various starches showed an effect on the emulsification of mayonnaise and enhanced rheological properties.

The stability and also rheological properties of low fat mayonnaise has an effect on the increase in the emulsification and viscosity of the mayonnaise regarding the amphipilic characteristics of these starch polysaccharides. Thaiudom and Khantarat (2011) conducted a substitution study of 50% starch sodium octenyl succinic acid (E1450) applied as a fat replacer in mayonnaise and conducted a study of mayonnaise the shelf life. The results affected several parameters including the higher viscosity value of SOS E1450 starch substitution, the smaller size of the fat droplet, prevented oxidation reactions and stable color consistency during the shelf life (Khantarat and Thaiudom, 2011).

The most recent study was arranged by Park et al. (2020) on the use of OSA-modified starch from arrowroot as a fat substitute for mayonnaise with 30% and 50% content. OSA modified starch was obtained by esterification with OSA in aqueous solution. Modification of the method had an effect on physicochemical characteristics, temperature and pasting properties. OSA starch generated better emulsion stability relative to the control (92.55-96.57%), a higher level of brightness at 50% substitution. Thus it can be concluded that OSA starch was suitable to be utilized as fat replacer for mayonnaise.

Cookies

Shortening is a kind of supplementary material often used in making bread or cakes. This material has a relatively high level of saturated fatty acids in it. Hadnađev et al. (2015) conducted a study regarding the use of OSA starch emulsions as a substitute for fat in cookie products. Low-fat formulations made from structured vegetable oils in the type of emulsions (50% and 70% O/W emulsions) were compared to the use of unstructured vegetable oils or without the addition of OSA starch. As a result, cookies made from OSA emulsions showed a stronger level of dough firmness indicated by the elastic modulus of the dough and lower cookie spread compared to the use of unstructured vegetable oil. However, despite having relatively healthier and sensory-accepted nutritional content, cookies made from OSA emulsions were still unable to compete with cookies made from traditional shortening.

Muffins and the like

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Muffins are typical cakes from England which are usually consumed as breakfast. Some ingredients often used in this cake include butter, eggs, and milk so that this cake is considered to have a relatively high level of fat. To reduce fat content, a study conducted by Chung et al. (2010) regarding partial substitution of fat with OSA starch and maltodextrin. OSA starch from dry-heated waxy corn (DH-OS) has been shown to generate higher specific volumes and a softer muffin texture relative to those generated from the addition of maltodextrin. In addition, at 40% butter substitution in muffin making, DH-OS starch prepared under acidic condition (pH 4) created the best volume of muffin. Meanwhile, DH-OS starch prepared at pH 6 generated muffins with the softest texture compared to DH-OS which was prepared under both acidic and basic conditions. The findings evidenced the effect of pH on the cake produced. On the other hand, muffins generated from DH-OS emulsions with a degree of stability of 0.0057 were proven to obtaine the best texture and had the most similar characteristics to full-fat muffins.

Punia et al. (2019) also conducted another study regarding the use of OSA starch modified from mung bean flour in cake formulation as a fat substitute compared to native starch. As a result, cakes made from OSA starch had a higher viscosity (pasting viscosity) and specific volume than the native starch. The use of 30% OSA starch for baking ingredients also gave good texture, color, and mouthfeel with a high level of sensory acceptance.

Low-calorie bread

OSA modified starch can be applied as an emulsifying agent or a fat substitute material in bread products. OSA modified starch also changes starch levels with slow digestibility and is resistant as part of the benefits of starch that can survive to be digested in the human digestion. Balic et al. (2016) conducted a study on low-calorie bread formulation using OSA starch as a fat replacer by 4% OSA modification from wheat and tapioca starch. OSA starch emulsions had an effect on the final bread product quality including increasing the bread volume, the color of the bread crumbs, and its softness since this OSA modified starch formed an amphiphilic molecule that had hydrophobic characteristic without modification so that the starch could absorb water and oil surfaces and stabilized the emulsion. The results evidenced that the characteristics of bread dough with the involvement of OSA modified starch from tapioca and wheat were better than the control of 2% shortening. Besides that OSA modified starch also raised the viscosity value with the highest swelling value indicated by 4% OSA, the same finding was shown from the result of the value bread absorption, 4% OSA modified starch, either wheat or tapioca showed higher values than the control of 2% shortening and faster mixing time than control. Broadly speaking, the contribution of OSA starch improved the characteristics ranging from gel firmness, pasting properties, stiffness to mixing properties, and the dough firmness. But when compared to its performance aspect, the better bread characteristics formation was by adding OSA modified tapioca starch compared to modified wheat starch.

Apart from being a fat replacer, OSA starch can also partially replace the role of flour. The application of OSA starch as a non-full substitute for wheat flour in bread making was carried out by Hadnađev and co-authors in 2014. In his study, 10% of wheat flour was replaced with three kinds of commercial OSA starch: normal and pre-gelatinized and hydrolyzed. Substitution carried out with the three types of OSA starch was able to produce a specific volume higher than full-wheat bread, the best outcome was obtained from pre-gelatinized OSA starch.

Ice cream

Fat substitution can also be done on some ice cream products. Sharma et al. (2016) conducted a trial using pearl millet (*Pennisetum typhoides*) starch which was esterified with OSA as a fat substitute for soft ice cream and compared with other types of fat substitute foods such as whey-70 protein concentrate, inulin, and commercial starch. The result showed that a mixture of soft ice cream (7.5 and 5% fat, from reference product of 10% fat) containing OSA starch of 1% and 2% succeeded to be comparable with other fat replacers such as inulin, whey protein concentrate, and also starch circulated in markets in terms of sensory reception, overrun, and melting characteristics. In addition, ice cream made from OSA starch was considered to provide a healthier option which had a higher resistant starch content.

Non-fat frozen milk dessert

Chiu et al. (1998) applied OSA modified starch which is widely utilized as an emulsion agent in food. Starch was esterified using octenylsuccinic acid to produce 0.25% - 3.0% esterified starch. Waxy corn starch was reacted with 1% octenyl succinic anhydride obtained 23% yield. The study was registered in the American patent by characterizing non-fat frozen milk dessert, the result of viscosity at overrun was 80.1 and after cooling was 51.7.

Hydrogel particles

Electrostatic complexation-based hydrogel particles have the potential to be used in encapsulation system. Wu et al. (2015) conducted a study which aims to make hydrogel microspheres from gelatin-modified starches and OSA starch for the use of fat droplets or mimetic starch granules. Mixture of 0.5% gelatin and 0-2.0% OSA starch mixed in water at room temperature under acidic pH conditios 5, characterization of formation and nature of electrostatic complexity through pH regulation, formations formed by OSA with gelatin so that it can be useful information to prepare fat droplets or Mimetic starch granules using healthier and cheaper raw materials. The results showed that reaction conditions and also the interaction between OSA and starch gelatin influenced the variations in the hydrogel particles shape. The hydrogel particles formed were beneficial as texture modifier or encapsulation of lipophilic molecules to generate better sensory quality of products with low calorie.

Table 2 Applications and results of using OSA starch as a fat replacer in food

Product	Source of starch	Effect on products	Reference
Minas fresh cheese	Waxy corn	OSA starch formulation of 0.5kg/100L had an effect on the chemical composition of fresh cheese with higher protein level and water level while lower fat level was higher than control, cheese texture was harder and more chewy relative to control	Diamantino et al. (2014)
Mayonnaise	Waxy corn	OSA starch (10g in 70g of sample) could form a stable emulsion using a hydrocolloid emulsifier to a fat content of 60% wt. In addition, higher fat content and increased amount of starch granule sediments could increase long-term stability.	Chivero et al. (2006)
	Potato	The best comparison between OSA starch and egg yolk was 75/25 based on the results of rheological test. In addition, no significant differences were found based on sensory evaluation in mayonnaise samples (75% and 100% substitution) after one month in relation to taste, color, odor, texture and appearance and control with cholesterol levels reduced by 84% to 97%.	Ghazaei et al. (2015)
	Arrowroot	OSA modified arrowroot starch as a substitute for 30% and 50% fat in mayonnaise. Modified methods had an effect on physicochemical characteristics, temperature and pasting properties. In general, OSA arrowroot starch had dissolved mayonnaise emulsion stability better than control.	Park et al. (2020)
	White sorghum and corn	Substitution of 75% fat by OSA modified sorghum and corn starch showed a high level of acceptance compared to control with	Ali et al. (2015)

		the texture attribute value of OSA modified sorghum starch that was not significantly different from full fat mayonnaise.	
	Wheat, waxy corn, potato, sweet potato, rice flour and kidney beans	OSA modified starch from various sources of starch was applied in 75% fat substitution. The viscosity of mayonnaise substituted by OSA starch was higher than without OSA starch. In addition, this substitution effect influenced the emulsification nature of mayonnaise, enhanced rheological and sensory properties which were still acceptable to panelists.	Bajaj et al. (2019)
	Commercial OSA starch (E1450)	The amphipilic characteristics of these starch polysaccharides enhanced the emulsification and viscosity of the mayonnaise. Substitution of 50% OSA starch could be applied as a fat substitute and stabilized rheological properties, color consistency, prevent oxidation reaction and product stability during the product storage period.	Thaiudom and Khantarat (2011), Khantarat and Thaiudom (2011)
Salad dressing	Waxy potato and waxy rice	It was proven that OSA debranched starch was more effective than OSA granule starch which experienced a significant decrease in quality over 3 days of storage. In fact, the substitution of 95% soybean oil using OSA debranched starch was able to give results that have the similar quality to commercial salad dressings and could last up to 90 days of storage.	Klaochanpong et al. (2017)
Cookies	Waxy corn	Cookies made from OSA emulsions as shortening agents had stronger dough firmness and lower cookie spread than the use of unstructured vegetable oils. However, despite having relatively healthier and sensory-accepted nutritional content, cookies made from OSA emulsions were still unable to compete with cookies made from traditional shortening.	Hadnađev et al. (2015)
Muffins	Waxy corn	OSA starch from dry-heated waxy corn (DH-OS) was shown to produce higher specific volumes and a softer muffin texture than those produced with the addition of maltodextrin. In addition, muffins produced from DH-OS emulsions with a degree of stability (DS) of 0.0057 were proven to produce the best texture and had the most similar characteristics to full-fat muffins.	Chung et al. (2010)
Bread	Tapioca and wheat	The characteristics of bread dough with the addition of OSA starch were better than the	Balic et al. (2016)

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		control of 2% shortening. Bread dough showed the better value of viscosity, absorption value and faster mixing time relative to the control. OSA starch improved the characteristics ranging from gel firmness, pasting properties, dough firmness and stiffness to mixing properties. In general, the performance of OSA tapioca modified starch was better than wheat modified starch.	
Cake	Mung bean	Cake made from OSA starch had a higher viscosity and specific volume than the native starch. Moreover, 30%OSA starch for baking ingredients also resulted in a good texture, color, and mouthfeel with a high level of sensory acceptance.	Punia et al. (2019)
Dessert (non-fat frozen milk)	Waxy corn	Application of OSA starch was carried out in the characterization of non-fat frozen milk desserts, the result of viscosity at overrun was 80.1 and after cooling was 51.7.	Chiu et al. (1998)
Ice cream	Pearl millet	A mixture of soft ice cream (7.5 and 5% fat, from reference product of 10% fat) containing OSA starch of 1% and 2% succeeded to be comparable with other fat replacers such as whey protein concentrate; inulin and commercial starch in terms of sensory reception, overrun, and melting characteristics. In addition, ice cream made from OSA starch was considered to provide a healthier option which had a higher resistant starch content.	Sharma et al. (2016)
Hydrogel microspher	Gelatin and commercial OSA starch	A mixture of 0.5% gelatin and 0-2.0% OSA starch was mixed in water at room temperature under acidic pH condition of 5. Neutrality of charge could be achieved when the ratio of OSA-gelatin starch was 4: 5. The hydrogel particles formed were beneficial as texture modifier or encapsulation of lipophilic molecules to generate better sensory quality of products with low calorie.	Wu et al. (2015)

In the last decade, publications related to OSA starch synthesis, its characterization and application in food products have continued to increase. The OSA starch synthesis method with aqueous media was the most widely utilized technique. The pre-treatment method was introduced to find the best reaction efficiency to gain OSA starch with a high degree of substitution. The presence of conjugate bonds with the octenyl succinate group in starch polymers could produce an amphiphilic starch characteristic so as to have an emulsifying function. OSA starch has a high affinity power to reduce surface tension in water, which is an important factor for making stable emulsions. Emulsions generated from OSA starch were utilized as fat replacers in foods with high fat content. OSA starch also has good pasting properties. The pasting characteristic is strongly influenced by the pre-treatment method applied.

Partial OSA starch substitution was successfully utilized as a fat replacer for several types of food products with similar sensory attributes or even slightly better than the native product (control). The resulting product could be defined as a healthier choice because it had relatively lower fat and calorie content. Even so, various adjustments through further study are still needed so that the food produced is able to have a higher level of sensory acceptance to native food without fat substitution. The study of the mechanism of OSA starch as a fat replacer needs to be conducted in the future. Information on any factors that influence the functionality of OSA starch as a fat replacer in many types of specific food matrix complexes also needs to be explored in the future.

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