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Characterization of the effects of chia gels on wheat dough and bread rheology as well as the optimization of bread roll production with the Nelder-Mead simplex method

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Statuory declaration and statement

1. For the dissertation submitted on the topic **„Characterization of the effects of chia gels on wheat dough and bread rheology as well as the optimization of bread roll production with the Nelder-Mead simplex method“** I hereby declare that I independently completed the work.

2. I only used the sources and aids documented and only made use of permissible assistence by third parties. In particular, I properly documented any contents which I used - either by directly quoting or paraphrasing - from other works.

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I hereby confirm the correctness of the above declaration: I hereby affirm in lieu of oath that I have, to the best of my knowledge, declared nothing but the truth and have not omitted any information.

Stuttgart-Hohenheim, den 10.06.2016

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Chapter 1

Summary

1.1 Summary

Chia (*Salvia hispanica* L.) is becoming increasingly popular as ingredient for baked goods. The aim of the first part of this thesis was to investigate the influence of gel from ground chia on the rheology of different wheat dough systems and the resulting baked goods. The evaluated products were wheat bread and sweet pan bread. The effects of chia incorporated as gel in wheat bread dough as hydrocolloid were characterized using empirical and fundamental rheological methods and differential scanning calorimetry. To avoid competition of starch and ground chia with respect to the water uptake, chia was incorporated as gel. The gel was prepared of ground chia with 5 g/g and 10 g/g water, respectively. The doughs were prepared with 1-3 % chia related to the amount of wheat flour. The effects of gel from ground chia were studied also as fat replacer in sweet pan breads. The main focus of the work was to study the effects of the fat substitution on the dough rheology. The dough rheology was characterized using a rotational rheometer and a Rheofermentometer. The end products were evaluated with a texture analyser and two samples were additionally evaluated with respect to their fatty acid profile. The substitution was secondly addressed to reduce the total amount of fat in the product and to improve the nutritional value of the products regarding the fatty acid composition. The fat was replaced in four steps, and the ratio among the ingredients was held constant to ensure a better comparability.

Within this thesis it was shown that addition of gel from ground chia can affect wheat doughs and the resulting baked products in a positive way. The approach of using ground chia as gel seems to be fruitful to avoid competition between starch and chia with respect to the water uptake while the crumb formation during the baking process takes place. The evaluation of the pasting profiles of wheat flour suspensions with chia gel addition reinforced this assumption. The gel from ground chia affected the pasting properties in a way that the viscosities decreased with increasing amount of chia. The rheological properties of the doughs were affected in negative ways with respect to further processing by the addition of too high amounts of chia gel. The dough stability was reduced and the resulting baked products were less and irregular porous and therefore compact. All doughs showed weakening regarding the rheometer measurements, however the linear viscoelastic region was not affected. The

frequency sweep measurements showed for all doughs a decrease with increasing content of gel from ground chia. The creep-recovery tests of the sweet pan bread doughs revealed that the zero viscosity η_0 decreased and the creep compliance J_0 increased with increasing chia gel content. The weakening of the doughs may not absolutely be caused by the incorporated chia, but by the additional water. There seems to be a kind of interaction between ground chia particles, wheat flour constituents and water, because nearly the same results were achieved for 2 % and 1 % of ground chia with 5 g/g and 10 g/g water, respectively. These experiments lead also to the best results for incorporating gel from gound chia to wheat breads. The best results for sweet pan breads were obtained with 25 % fat replacement through gel from ground chia. This gel was prepared of 2.3 g ground chia with 5 g/g water. Summarizing the incorporation of defined amounts of gel from ground chia has a positive effect on the rheology and the resulting baked products. The retrogradation of the baked products was decreased over storage and the dietary fibre content was increased. Thus chia acts like a hydrocolloid. The nutritional values of the evaluated baked products, wheat bread and sweet pan bread, were increased. For the sweet pan breads an increase of ω-3 fatty acids was determined. The resulting best sweet pan bread exhibited an amount of 5 % linolenic acid. Gel from ground chia can therefore be incorporated into bakery products as hydrocolloid and for improving the nutritional values regarding the dietary fibre and ω-3 fatty acid contents.

Another part of the work was the optimization of the production parameters, proofing time and baking temperature, for bread rolls. The optimization was performed with the Nelder-Mead simplex method. The optimization was necessary for a new oven type, where the oven walls were coated with a ceramic, that increased the infrared radiation during the baking process. The quality criterion for the optimization were the specific volume, the baking loss, the colour saturation, crumb firmness as well as the elasticity of the bread rolls.

Within 11 experiments the optimal baking result defined by the results of a conventional oven was obtained. The optimal processing parameters for the bread rolls were a proofing time at 117 minutes and a baking temperature of 215 °C for 16 minutes.

1.2 Zusammenfassung

Chia (*Salvia hispanica* L.) wird als Zutat für Backwaren immer beliebter. Ziel des ersten Teiles dieser Arbeit war die Untersuchung des Effekts von Chiagelen auf unterschiedliche Teigsysteme und den daraus resultierenden Backwaren. Die untersuchten Backwaren waren Weizenbrot und Kastenstuten.

Zunächst wurden die Effekte von eingebrachtem Chiagel als Hydrokolloid in Weizenteig untersucht. Hierzu kamen empirische und fundamentale rheologische Methoden und die Dynamische Differenzkalorimetrie zum Einsatz. Um eine Konkurrenz von Stärke und Chia um das freie Wasser zu verhindern, wurde Chia als Gel eingebracht. Die Gele wurden mit geschroteten Chiasamen und 5 g bzw. 10 g Wasser pro g Chia erzeugt. Die Teige wurden mit 1 % bis 3 % Chia bezogen auf die Mehlmenge hergestellt. Anschließend wurden die Effekte von Chiagel als Fettersatz in Kastenstuten untersucht. Die Substitution des ursprünglichen Fettes sollte zum einen den Gesamtfettgehalt der Kastenstuten senken, aber auch die ernährungsphysiologische Qualität der Kastenstuten im Hinblick auf das Fettsäureprofil erhöhen. Das Fett wurde hier in vier Schritten ersetzt wobei die Gesamtteigmenge konstant gehalten wurde, um eine bessere Vergleichbarkeit der Ergebnisse zu gewährleisten.

Im Rahmen dieser Arbeit wurde festgestellt, dass die Addition von Chiagelen Weizenteige und die daraus resultierenden Backwaren in positiver Weise beeinflussen kann. Der Ansatz, die geschroteten Chiasamen mit Wasser vor zu verquellen und somit den Wasseranteil insgesamt zu erhöhen, erwies sich als sehr sinnvoll. Die Konkurrenz von Chia und Stärke um das im Teig zur Verfügung stehende Wasser konnte somit verhindert werden. Die Untersuchung der Verkleisterungseigenschaften hat diese Vermutung bestätigt. Die Chiagele verringerten die Viskositäten mit steigendem Chiagehalt. Die untersuchten Teige wurden hinsichtlich ihrer Weiterverarbeitbarkeit durch den Einsatz von zu viel Chiagel negativ beeinflusst. Die Teigstabilität wurde verringert und die resultierenden Backwaren waren sehr kompakt, da sie nur wenig und ungleichmäßig gelockert waren. Bei den Rheometermessungen zeigten alle Teige eine Erweichung, die Bereiche für die linear-viskoelastische Region wurden jedoch nicht beeinträchtigt. Die Frequenzsweep-Messungen zeigten verringerte Moduli für alle Teige mit steigendem Chiagelanteil. Die Kriecherholungsversuche der Kas-

tenstutenteige zeigten, dass die Nullviskosität η_0 abnahm. Die Kriechnachgiebigkeit nahm hingegen mit steigendem Chiagelanteil zu. Die Teigerweichung ist vermutlich nicht nur durch den Zusatz von geschroteten Chiasamen verursacht worden, sondern auch durch die höhere Menge an Wasser, die so mit in den Teig eingebracht wurde. Die Ergebnisse legen nahe, dass es eine Wechselwirkung zwischen geschroteten Chiasamen, Mehlbestandteilen und Wasser geben muss. Für die Backversuche mit 2 % Chia und 5 g/g Wasser und diejenigen mit 1 % Chia und 10 g/g Wasser wurden die gleichen Ergebnisse erzielt. Diese Backversuche zur Einbringung von Chiagelen in Weizenbrote führten zu den besten Ergebnissen. Für die Kastenstuten erwies sich eine Substitution von 25 % des Fettes durch Chiagel als sehr gut. Zusammenfassend lässt sich sagen, dass das eingebrachte Chiagel sich positiv auf die Rheologie der untersuchten Backwaren ausgewirkt hat. Die Retrogradation der Backwaren wurde verzögert und der Ballaststoffanteil in den Gebäcken wurde erhöht. Chia wirkt also auch als Hydrokolloid. Das Fettsäureprofil aller hergestellten Gebäcke wurde vermutlich im Bezug auf die ω-3 Fettsäuren verschoben. Für die Kastenstuten wurde diese Vermutung, auch beim Einsatz von nur 2.3 % Chia, bestätigt. Der Anteil an $\alpha-$Linolensäure betrug hier 5 %. Die ernährungsphysiologischen Eigenschaften beider Backwaren wurden durch den Einsatz von Chia erhöht. Chiagel kann folglich zur Steigerung der ernährungsphysiologischen Qualität bezüglich der Gehalte an Ballaststoffen und ω-3 Fettsäuren eingebracht werden.

Ein weiterer Teil der vorliegenden Arbeit war die Optimierung der Herstellungsparameter, Dauer der Endgare und Backtemperatur, für Brötchen. Die Optimierung wurde mit der Nelder-Mead Simplex Methode durchgeführt. Die Optimierung war für einen neuen Backofen erforderlich, dessen Wände mit einer speziellen Keramik beschichtet sind. Diese erhöht den Anteil an Infrarotstrahlung während des Backprozesses. Als Qualitätskriterien wurden das spezifische Volumen, der Backverlust, die Rösche, die Farbsättigung und die Krumenfestigkeit sowie -elastizität der Brötchen herangezogen.

Mit nur 11 Experimenten wurde das optimale Backergebnis erzielt, das anhand der Ergebnisse eines herkömmlichen Backofens definiert wurde. Eine Fermentationsdauer von 117 Minuten und der Backvorgang bei 215 °C für 16 Minuten wurden als optimale Herstellungsparameter bestimmt.

Chapter 2

Introduction and outline

2.1 Chia (*Salvia hispanica* L.)

The correct botanical name of chia is *Salvia hispanica* L. belonging to the Salvia category of the *Labiatae* family. It is a subtropical annual plant which requires less water compared to other crops. *Salvia hispanica* L. was an important staple Mesoamerican food and medical plant in pre-Columbian times (Cahill, 2003). Application of Salvia genus is common in flavouring and folk medicines worldwide (Lu and Yeap Foo, 2002). Chia seeds have been used as whole seeds, seed flour, seed mucilage, and seed oil. A refreshing drink made with whole chia seeds has attained great popularity in Mexico and beverages remain the major culinary use, however those made with flour have fallen out of favour, as has use of chia flour in general (Cahill, 2003; v. Schlechtental, 1830). The popularity of chia seeds increased rapidly in the last few years. They have been revalued due to their nutritious properties: high fibre, polyphenols and lipids content (Jiménez *et al.*, 2010). The number of publications about chia and its ingredients spread rapidly from 4 (2007) to 36 (2015) and 28 until June 2016 (compare with Table 2 in the Annex). Earlier publications refer to the botanical properties of chia, newer publications investigate mostly the application of chia in different products. Here the obtained mucilage when chia seeds are placed in water was the most interesting part.

Great potential for chia is seen as future crop plant. Chia requires less water than cereals or other oil seeds to grow, so it is also investigated as future crop for more diversity in Argentinia and the U.S. (Coates and Ayerza, 1996, 1998; Estilai *et al.*, 1996; Gentry *et al.*, 1990). As new ω-3 fatty acid source the flowering of chia was successful applied in the growing season 2009 in Kentucky for example (Jamboonsri *et al.*, 2011). Recent studies showed, that water stress leads to an increase of lipid and therefore ω-3 fatty acid production (Silva *et al.*, 2016). The evaluation of the chia seed oil was done by several authors (Álvarez-Chávez *et al.*, 2008; Ayerza, 1995; Bushway *et al.*, 1981; Estilai *et al.*, 1996; Ixtaina *et al.*, 2011; Steger *et al.*, 1942; Palma *et al.*, 1947; Taga *et al.*, 1984). Besides the oil the nutritional composition of chia is discussed (Bushway *et al.*, 1984; Llorent-Martínez *et al.*, 2013; Weber *et al.*, 1991). Furthermore the polysaccharide mucilage was studied for different applications (Gentry *et al.*, 1990; Gillet, 1981; Lin *et al.*, 1994; Whistler, 1982; Capitani *et al.*, 2013). Lin *et al.* (1994) determined a linear tetrasaccharide that contains 25 % uronic acid. Like pectin (D-galacturonic acid) uronic acids are commonly used as gelling agents in food technology.

2.1.1 Chia (*Salvia hispanica* L.) in food applications

Since 2009 chia is allowed in breads up to 5 % in context of the novel food regulation of the EU (EC, 2009). The commission implementing decision in January 2013 (EC, 2013) extended the use of chia as novel food ingredient. Baked products, breakfast cereals and fruit, nut and seed mixes must not contain more than 10 % chia, the daily intake of chia should not exceed 15 g. The chia seeds were known earlier in Germany for their mucilage release when placed in water (v. Schlechtental, 1830).

Nutritional properties of chia

Chia seeds are nutritionally valuable (Ayerza and Coates, 2011; Ixtaina *et al.*, 2008; Llorent-Martínez *et al.*, 2013; Muñoz *et al.*, 2013; Marineli *et al.*, 2014). According to Martínez-Cruz chia could be incorporated in human diet as novel isoflavone source, because of its high antioxidant capacity (Martínez-Cruz and Paredes-López, 2014). The quality of chia seeds is affected by the genotypes (Cahill, 2004; Cahill and Ehdaie, 2005) and ecosystem conditions (Karim *et al.*, 2015; Ayerza, 2016). The identification of the origin of chia seeds is therefore also an important research area (Ayerza, 1995; Ayerza and Coates, 2011, 2009a,b). The purity of chia seeds is also a topic of interest. Bueno *et al.* (2010) found out that lots of chia seeds are adulterated, the physico-botanical purity of the seeds ranged thus between 0 % and 98.6 %, but there were no differences in the fatty acid content.

Dietary fibre

Reyes-Caudillo *et al.* (2008) determined the total of dietary fibre (TDF) content of chia seeds with 18–60 g/100 g. Total dietary fibre include polysaccharides, oligosaccharides, lignin and other associated substances. In accordance with these findings Vázquez-Ovando *et al.* (2009) determined the physiochemical properties of a fibrous fraction from chia. They confirmed the high content of TDF (56.46 g/100 g) composed mainly of insoluble dietray fibre (IDF)

(53.45 g/100 g) with a low content of soluble dietary fibre (SDF) (3.01 g/100 g) as described in the same range by different studies before (Reyes-Caudillo *et al.*, 2008; Salgado-Cruz *et al.*, 2013). Due to the composition of the chia seeds they form mucilage hydrated in water that could be used as industrial additive due to its outstanding physiochemical properties (Salgado-Cruz *et al.*, 2013). The incorporation of dietary fibre is most commonly to prolong freshness of baked products for their capacity to retain water. The water holding capacity of 15.41 g/g of chia fibre suggested a use as hydrocolloid (Vázquez-Ovando *et al.*, 2009). The water absorption process of chia seeds was evaluated by Moreira *et al.* (2010).

According to the European Food Safety Authority (EFSA) the fibre intake for adults of 25 g/day is adequate for normal laxation. Greater intakes reduce risks of coronary heart disease and type 2 diabetes and improved weight maintenance (EFSA Panel on Dietetic Products, Nutrition and Allergies, 2010). The American Dietetic Association advises for developing countries 60–120 g/day and that the insoluble (IDF)/soluble (SDF) ratio of dietary fibre should be 3:1. Fibre as a functional food ingredient may be considered to possess two kinds of properties: (a) technological functionality and (b) physiological functionality. Properties vary widely depending on the type of fibre (Borderías *et al.*, 2005). The protein content of chia seeds, obtaining a good balance of essential amino acids, was evaluated by Sandoval-Oliveros and Paredes-López (2013).

Positive effects on human health are reported by several authors (Toscano *et al.*, 2014; Vuksan *et al.*, 2010; Salgado-Cruz *et al.*, 2014; Altamirano *et al.*, 2015). After a double blinded, parallel and randomized study Jenkins *et al.* (2016) suggested chia as as supplement in conventional therapy for overweight and obesity in diabetes, because of the glycemic control and the promoted weight loss by consuming chia. However, according to Ulbricht *et al.* (2009) the efficacy of *Salvia hispanica* for any indication is not proven yet. More examinations on the use of chia as dietary supplement as well as the treatment or prevention on human diseases are needed.

Fatty acid composition

The promising fatty acid composition of chia seeds is another well studied topic. Ayerza and Coates (Ayerza and Coates, 2005; Ayerza Jr. and Coates, 2007) carried out feeding experiments with ground chia seed and chia oil on rats. The results show an increase of HDL cholesterol and ω-3 fatty acid contents, with a significant improvement in n-6/n-3 fatty acid ratio, in rat serum. Chia seed oils were characterized by Álvarez-Chávez *et al.* (2008) as attractive source of α-linolenic acid and phytosterols in comparison with other vegetal sources actual used. They evaluated chia seed oils of two different chia seeds cultivated in different regions. The average oil content was (25.5 $\pm$ 4.55) % and (29.7 $\pm$ 4.05) %, respectively, with α-linolenic acid accounting for about 62 % of the total fatty acid methyl esters in the oil. All authors concluded that chia oil, rich in α-linolenic acid, might be an alternative ω-3 fat source for vegetarians and people allergic to fish and fish products. The safety and efficacy of chia is discussed by Mohd Ali *et al.* (2012). They concluded that chia seed oil can maintain a balanced serum lipid profile, but that there is some more research needed to do a correct safety evaluation. Citelli *et al.* (2016) showed that chia oil supplementation changes the lipid serum profile in liver, but does not change the total weight of the participants. Albert *et al.* (2005) support the hypothesis that ω-3 fatty acids through an increasing dietary intake of α-linolenic acid might reduce the risk of sudden cardiac death. Low proportions of chia oil addition (10 % and 20 % weight percentage) on sunflower oil lead to a essential fatty acid balance (Guiotto *et al.*, 2014).

2.1.2 Applications

Chia is used as whole chia seeds and chia flour or ground chia, soaked in water or dry. Depending on the application only the mucilage or the oil of chia are used for further processing. To obtain ground chia or chia flour different methods are described. Because of the high oil content the milling of the seeds leads to problems regarding the quality of the fatty acids. Different authors used different methods to grind the chia seeds like double knife crusher (Coelho and Salas-Mellado, 2015), stainless steel grinder (Verdú *et al.*, 2015; Zettel *et al.*, 2015), or analytical mills (Luna Pizarro *et al.*, 2013, 2015; Rendón-Villalobos *et al.*, 2012;

Inglett and Chen, 2014). Milled, ground chia seeds or flour are commercial available in many countries in the meantime.

Baked goods

Baked goods are easy to modify and different authors use chia to improve them. Ground chia is recently used as additive to bakery products like pound cake and bread. Chia is used there as whole seed, soaked or dry, or as ground chia or chia flour. The main goal is the nutritional improvement of baked goods. Costantini *et al.* (2014) were substituting 10 % wheat flour with chia flour in wheat bread. They obtained no change in the specific volume or the total flavonoid content of the breads, but an increase in moisture, fat, dietary fibre and total phenolic content, and a decrease in carbohydrate content. The amount of linoleic acid and linolenic acid increased from (0.40 ± 0.02) g/kg of total fatty acids on dry weight (DW) to (19.3 ± 1.2) g/kg of total fatty acids on DW and (0.03 ± 0.01) g/kg of total fatty acids on DW to (61.8 ± 2.4) g/kg of total fatty acids on DW respectively. The total antioxidant activity was many times higher than in the control wheat bread. Luna Pizarro *et al.* (2013) investigated the effects of adding whole chia flour (WCF) and hydrogenated vegetable fat (HVF) on the technological, nutritional and sensory qualities of cakes. The best cake formulation contained 15 g WCF/100 g flour mixture and 20 g HVF/100 g flour mixture and had higher lipid, ash and protein contents than the control cake. A considerable increase in its ω-3 fatty acid content and good sensory acceptance were accompanied there with a greater purchasing intention of consumers. The application of chia gel as fat or egg replacer in cake formulations was evaluated by Borneo *et al.* (2010). The replacement of 25 % egg or oil resulted in a more nutritious product with acceptable sensory characteristics. Fat was also reduced by application of chia mucilage gel in pound cakes (Felisberto *et al.*, 2015). Best results were achieved with 25 g chia mucilage gel per 100 g of fat. Coelho and Salas-Mellado (2015) reduced the additional fat in the bread baking process and substituted wheat flour with chia flour and seeds. The reduction of the fat content of the bread was 27 % obtained with 7.8 g/100 g chia flour and 24 % with 0.9 g/100 g fat and 11 g/100 g chia seeds and 1 g/100 g fat respectively. The content of dietary fibre and ω-3 fatty acids was increased in the resulting products. Consumer acceptance tests revealed that there was no significant ($p > 0.05$) difference between the control and the 25 % chia muffin and for the cookie control and the 5 % ground 10 % whole chia cookie sample (Lewis, 2010). The dietary fibre content of white breads was increased about 50 % compared to the control by chia seed addition (Švec and Hrušková, 2015). The changes in dough viscoelastic properties and the worsening of the quality and therefore consumer acceptance were however small.

Besides the improvement of the nutritional values the technological influence on wheat bread was investigated by different authors. The effect of chia seed flour on each wheat bread-making phase and product storage was investigated by Verdú *et al.* (2015). Wheat flour was here substituted by chia seed flour at 5 %, 10 % and 15 %. The gas retention and the dough growth was improved by chia addition. The bread freshness was prolonged, detected with less crumb hardness and a delay in water loss.

The physical properties of chia seeds are affected by their moisture content (Guiotto *et al.*, 2011). The effect of pre-hydration of chia seeds and flour on the quality of wheat flour breads was determined by Steffolani *et al.* (2015). With pre-hydration the volume remained unchanged at 10 g/100 g_{flour} chia addition, without pre-hydration a decrease was observed. Iglesias-Puig and Haros (2013) investigated the performance of dough and bread with incorporated chia seeds, flour and modified flour. They concluded that the incorporation of chia inhibited the kinetics of amylopectin retrogradation during storage. Negative effects on the resulting end product were reported by Luna Pizarro *et al.* (2015), although a better ω-6/ω-3 ratio was achieved with a high amount of ω-3 α-linolenic acid. The gluten network was weakened by 10 % whole chia flour addition, but the effect could be attenuated by the addition of vital gluten. All studies conclude that the mucilage is influencing the water-holding capacity and is in interaction with the protein network. It is also sometimes concluded that the retrogradation of the breads is delayed by adding chia. Chia acted in these experiments thus like a hydrocolloid. The application as hydrocolloid was also proposed by Capitani *et al.* (2015). Farrera-Rebollo *et al.* (2012) developed an image analysis tool for sweet bread crumb structures with the help of incorporated chia flour. He could show the chia particle distribution by his image analysis system.

Glutenfree diet

Chia is also used in glutenfree diet especial breads, to enhance the nutritional quality. The combination of chia with other nutritional valuable raw materials results in promising applications (Constantini, 2015; Moreira *et al.*, 2013). Constantini *et al.* (2014) were substituting 10 % buckwheat flour with chia flour in glutenfree bread. They obtained no significant change in the specific volume, but an increase in moisture, fat, dietary fibre content, and a decrease in carbohydrate content. The amount of linoleic acid and linolenic acid increased. Corn tortillas with reduced glycemic index and significant higher levels of protein, lipids and total dietary fibre were produced with 15 % and 20 % addition of milled chia flour (Rendón-Villalobos *et al.*, 2012). Chia flour was also used for rice and soy based glutenfree breads. Here parts of the flours and the hydrocolloid (HPMC) were substituted with 2.5 % chia flour with no significant differences to the standard (Huerta *et al.*, 2016).

Other products – functional food, hydrocolloid, thickener

For functional food applications new substances with high gelling and emulsion stability are needed. Improved nutritional values by combining chia with other important cereals were evaluated by Inglett *et al.* (Inglett *et al.*, 2013; Inglett and Chen, 2014; Inglett *et al.*, 2014). They proposed these obtained gels with high gelling abilities and emulsion stabilities for functional foods. Spada *et al.* (2014) produced soy based desserts with chia mucilage as thickener. The resulting desserts differed in rheology and therefore consistency, but not in colour, flavour and creaminess. They concluded that the addition of mucilage chia can be made without causing major changes to the product. Oil in water emulsion gel containing chia could replace animal fats in the formulation of healthier meat products (Pintado *et al.*, 2015). Chia mucilage is discussed as functional ingredient and as stabilizer or thickener agent in emulsions. In combination with sunflower lecithin stable emulsions could be produced by Guiotto *et al.* (2016). Chia protein hydrolysates incorporated in white bread and carrot cream lead to products with improved ACE inhibitory activity (Segura-Campos *et al.*, 2013). Goh *et al.* (2016) concluded that the 'weak' viscoelastic, strong shear dependent gel might provide potentially useful rheological properties in food systems.

2.1.3 Conclusion

Chia is the topic of many research studies. The characterization of the mucilage and the effects of chia in different applications are well studied. The effects of chia consumption on the human health need more research to get a correct safety evaluation. The origin of chia seeds and the determination of the quality of these seeds is also a big issue, because the consumers should not be misled by wrong promises of chia in food applications. In conclusion the application of chia in baked goods can subsequently reduce the intake of saturated fats and increase the intake of ω-3 fatty acids, which are essential for the human diet. Furthermore the amount of dietary fibre can be increased which leads to a reduced risk for different diseases. The application as food thickener or hydrocolloid is also promising.

2.2 Yeast leavened baked wheat products

Wheat is worldwide the number three of staple foods (Klingler, 2010). The harvest yield for wheat was in 2015 123,500 kt in the European Union. The worldwide production was 725,471 kt, the worldwide consumption of wheat was 704,908 kt in 2014/2015 (Foreign Agricultural Service/USDA, Office of Global Analysis, 2016). Wheat flour is for example used for bread making and sweet snacks and viennoiserie. Wheat dough systems are influenced by different ingredients. According to the guidelines for bread and bakery products and the guidelines for fine bakery products (German Food Code Commission (DLMBK)) different aspects need to be considered. The amount of fat and sugar is regulated for bread to less than 10 parts of 90 parts milled cereal products. For fine bakery products it has to be more than 10 parts. Fat and sugar influence the dough developing during the fermentation process of yeast leavened dough systems. In this thesis only yeast leavened doughs are evaluated. The yeast activity is additionally influenced by the amount of water used for dough preparation (Mastromatteo *et al.*, 2013).

2.2.1 Dough characterization

The wheat doughs can be characterized with different measurement methods commonly used in cereal science. For the production of wheat breads the optimal amount of water is usually determined with the help of Farinograph measurements. To obtain information about the dough stability and the gas retention capacity of the dough systems Rheofermentometer measurements are performed. The dough viscosity and elasticity is commonly evaluated by oscillatory rheometer measurements. Here amplitude sweeps and frequency sweeps are performed. Creep-recovery tests are performed to get information of the flow ability of the dough at the end of applied load (zero viscosity η_0) and the instantaneous deformation (creep compliance) of applied load.

The dough elasticity is also commonly determined by using the Kieffer dough and gluten extensibility rig. This measurement can be performed with a texture analyser. The pasting properties of flour or starch mixtures are usually determined with a Rapid Visco Analyser as described in ICC standard 162 (ICC, 1996).

2.2.2 Evaluation of the baking experiments

The evaluation of baking experiments is usually performed after the cooling of the baked products to room temperature and after previously defined storage times in plastic bags at defined temperatures. The cooling period is defined depending on the size of the product. The evaluation of the baked goods is done by typical characteristics for baking like volume yield, specific volume and baking loss. The baking loss is calculated as mass difference between initial dough mass and baked bread divided by the initial dough mass. The volumes of the baked goods can be determined according to the AACC Method 10–05 (AACC, 2000) rapeseed procedure, based on a volume displacement system or with a laser-based volume scanner. With the obtained volume the specific volume is calculated by dividing the volume by the mass of the baked good.

Texture profile analysis (TPA) is performed with a modified AACC method (74-09) (AACC, 2000) to evaluate the crumb firmess and springiness of the baked products. After storage the measurements are conducted to determine the freshness of the baked goods. Differential scanning calorimetry (DSC) is applied for determining the retrogradation of the wheat breads over storage period.

The nutritional evaluations of baked goods include usually determining protein, ash, carbohydrate and fat content, as well as sometimes the fatty acid profile.

2.3 Nelder-Mead simplex optimization

Process optimization has been carried out as long as processes are performed. Normally statistical design of experiments is used. The response surface methodology for example is well established for food processes (Flander *et al.*, 2007; Turabi *et al.*, 2007; Therdthai *et al.*, 2002; Collar *et al.*, 1999; Lahlali *et al.*, 2008; Getachew and Chun, 2016; Liu *et al.*, 2016). As an alternative for optimization a sequential approach is the Nelder-Mead simplex method (Nelder and Mead, 1965), which was originally applied for the minimization of a function.
The simplex method according to Nelder-Mead is a fast and straight forward method well etablished in chemical industry (Cerdà *et al.*, 2016). Using the simplex method parameters can be optimized within few steps by minimizing or maximizing a quality or objective function (Spendley *et al.*, 1962). It can be performed within arbitrary dimensions. For two dimensions three starting experiments are needed. The starting experiments must be independent of each other. The starting experiments are rated and the worst experiment $\vec{w}$ will be mirrored on the mass centre $\vec{M}$ of the best $\vec{b}$ and the good $\vec{g}$ assessed experiment. The calculation for the new experimental point $\vec{n}$ is performed using Equation 2.1:

$$\vec{n} = \vec{M} + \gamma \cdot (\vec{M} - \vec{w}) \tag{2.1}$$

$$\vec{M} = \frac{1}{2} \cdot (\vec{g} + \vec{b}) \tag{2.2}$$

γ is the expanding/contracting factor depending on the last four experiments. This factor can be -0.5, 0.5, 1 and 1.5 depending on the values of the quality function of the new (QF_n) performed experiment with respect to the former best (QF_b), good (QF_g), and worst (QF_w) outcome (see Table 1).
Depending on these cases the next experiment is calculated. For instance, if the outcome (QF_n) of the new experiment $\vec{e}_n$ is better than the best outcome before $\vec{e}_b$ (which means $QF_n < QF_b$) the expanded simplex has to be applied. Therefore, the next experiment will be calculated using $\gamma = 1.5$ in Equation 2.1. The triangles might be getting smaller with every second iteration and approach to the optimum (Mathews and Fink, 1999).

Table 1: Cases for the evaluation of the new performed experiment. Goal: Minimization of the quality function.

case		Name (index)	γ
1	$QF_n < QF_b$	expanded simplex (e)	1.5
2	$QF_b < QF_n < QF_g$	normal simplex (n)	1
3	$QF_g < QF_n < QF_w$	contracted simplex (c)	0.5
4	$QF_w < QF_n$	negative contracted simplex (nc)	-0.5

The quality function can be chosen depending on the needs of the final goal. It is possible to weigh important characteristics statistically, but equally weighting is possible.

A detailed description of the Nelder-Mead simplex method is given by Bezerra *et al.* (2016) and Cerdà *et al.* (2016).

2.4 Aims of the thesis and outline

The aims of the thesis and subsequently the results section are divided in three parts. The first two parts discuss the influence of chia gel on the rheology of different wheat dough systems and the resulting baked goods. The third part presents an alternative optimization method for food processes.

Chia (*Salvia hispanica* L.) is becoming increasingly popular as ingredient for baked goods. Many authors conclude that the application of chia in baked goods can subsequently reduce the intake of saturated fats and increase the intake of ω-3 fatty acids, which are essential for the human diet. Furthermore, the amount of dietary fibre can be increased which leads to a reduced risk for different diseases.

The first presented contribution evaluated the technological effect of gel from ground chia for wheat dough processing and its influence on the shelf life of wheat breads. Chia has high water absorption and holding capacity. To avoid competition of starch and ground chia, chia was incorporated as gel. The amount of water (5 on 1) for gel preparation was chosen to get a gel with a good stability based on the results of Inglett and Chen (2014). The second ratio of water to chia (10/1) was performed to find out to what extent the gel composition affects doughs.

In the second contribution the effect of fat replacement by gel from ground chia was investigated. The purpose of this study was to prepare sweet pan bread with chia as partial fat replacer with respect to its effect on the rheological behaviour on the prepared doughs and the resulting end products. Another minor aspect was to obtain a better fatty acid profile resulting in a higher nutritional value for these sweet baked goods. The effects of the incorporated ground chia were investigated regarding the baking results, shelf life and fatty acid composition for the most promising sample. The fat was replaced in four steps, and the ratio among the ingredients was held constant, so that every bread had the same dough mass.

Using the Nelder-Mead simplex method for the optimization of production parameters of bread rolls is discussed in the third part of the presented thesis. It is an alternative optimization method for food processing.

The response surface method is well established in this area. The Nelder-Mead simplex method is well established in chemical processes. However the Nelder-Mead simlex method was not applied for the optimization of food processes yet. The approach was to use a standard production process in cereal technology, here the implementation of a bread roll production for a new oven with different baking characteristics. These have been studied before (Zettel *et al.*, 2016). The main advantage of the Nelder-Mead simplex optimization is that just few experiments are necessary to get optimal results. Another advantage was seen in the iterative proceeding of the method with the evaluation of every experiment. Using the response surface method all experiments have to be performed before the overall evaluation of the experiments followed by the optimization could be performed.

The aim was then to find out if the Nelder-Mead simplex method could be implemented in cereal technology. Bread rolls were processed according to the standard procedure. The proofing time and the baking temperature were modified during the optimization process. The quality was determined according to a standard defined by baking experiments in a conventional oven. Quality characteristics for bread rolls were the specific volume, the baking loss, the crust colour saturation, the crispiness and the crumb hardness and elasticity.

Chapter 3

Results

3.1 Influence of gel from ground chia (*Salvia hispanica* L.) for wheat bread production

The following contribution evaluates the influence of gel from ground chia on wheat dough and the resulting bread. The effects of chia incorporated as gel in wheat bread dough as hydrocolloid were characterized. To avoid competition of starch and ground chia with respect to the water uptake, chia was incorporated as gel. Other studies revealed for example, that the incorporation of dry ground chia results in a negative way for the moisture content of the crumb of the baked good and the freshness was subsequently decreased. The gel was prepared of ground chia with 5 g/g and 10 g/g water, respectively. The doughs were prepared with 1-3 % chia related to the amount of wheat flour. To characterize the dough, measurements with a Farinograph, a Rheofermentometer and a Kieffer dough and extensibility rig were performed. The pasting curves of all variations were recorded with a Rapid Visco Analyser. The fundamental rheological characteristics were determined with tests using a rotational rheometer. Baking experiments were performed to evaluate the effect of chia gel addition on the bread quality. The staling and crumb firmness were analysed by differential scanning calorimetry and texture analysis.

Dough analyses show that the doughs with added chia gel have a softer consistency. Dough stability during fermentation and volume yield of the bread loafs increased with added chia gel to a certain extent. These changes are visible with already 1 % chia. The bread quality was improved with respect to storage as the crumb firmness was reduced compared to the breads without added chia gel.

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ORGINAL PAPER

Influence of gel from ground chia (*Salvia hispanica* L.) for wheat bread production

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Abstract The effects of chia incorporated as gel in wheat bread dough as hydrocolloid were characterized. To avoid competition of starch and ground chia, chia was incorporated as gel. The gel was prepared of ground chia with 5 and 10 g/g water, respectively. The doughs were prepared with 1–3 % chia related to the amount of wheat flour. To characterize the dough, measurements with a Farinograph, a Rheofermentometer and a Kieffer dough rig were performed. The pasting curves of all variations were recorded. The fundamental rheological characteristics were determined with tests using a rotational rheometer. Baking experiments were performed to evaluate the effect of chia gel addition on the bread quality. The staling and crumb firmness were analysed by differential scanning calorimetry and texture analysis. Dough analyses show that the doughs with added chia gel have a softer consistency. Dough stability during fermentation and volume yield of the bread loafs increased with added chia gel to a certain extent. These changes are visible with already 1 % chia. The bread quality was improved with respect to storage as the crumb firmness was reduced compared to the breads without added chia gel.

Keywords Chia · Wheat dough · Rheology · Staling · DSC · Texture analysis

Introduction

Chia (*Salvia hispanica L.*) is a subtropical annual plant belonging to the *Laminaceae* family. Chia seeds are nutritionally valuable [1, 2]. Chia seeds contain a total of dietary fibre TDF (18–60 g/100 g) [3] that include polysaccharides, oligosaccharides, lignin and other associated substances. According to the European Food Safety Authority (EFSA), the fibre intake for adults of 25 g/day is adequate for normal laxation. Greater intakes reduce risks of coronary heart disease and type 2 diabetes and improved weight maintenance [4]. The American Dietetic Association advises for developing countries 60–120 g/day and that the insoluble (IDF)/soluble (SDF) ratio of dietary fibre should be 3:1 [5]. Fibre as a functional food ingredient may be considered to possess two kinds of properties: (1) technological functionality and (2) physiological functionality. Properties vary widely depending on the type of fibre [5]. Vázquez-Ovando et al. [6] determined the physiochemical properties of a fibrous fraction from chia. They confirmed the high content of TDF (56.46 g/100 g) composed mainly of IDF (53.45 g/100 g) with a low content of SDF (3.01 g/100 g) as described in the same range by different studies before [3]. They concluded that the fibre-rich chia fraction could be a potential ingredient in health and diet food products such as powders, nutrition bars, breads and cookies. Due to the composition of the chia seeds, they form mucilage hydrated in water that could be used as industrial additive due to its outstanding physiochemical properties [7]. The incorporation of dietary fibre is most commonly to prolong freshness of baked products for their capacity to retain water. The main challenge of additional fibre in cereal products is the adverse effect on the end product quality [8]. Farahnaky et al. [9] isolated the mucilaginous hydrocolloids from *Salvia macrosiphon* and studied their functional properties, since many mucilaginous seeds have been found as accessible, cost-effective and natural sources for producing food hydrocolloids. Lin, Daniel and Whistler [10] determined a linear tetrasaccharide that contains 25 % uronic acid. Like

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Table 1 Wheat dough formulations, all ingredients are related to the amount of wheat flour (100 %)

Ingredient	Farinograph	Kieffer dough rig	Rheofermentometer	Baking experiments
Wheat flour (g)	300	50	200	1100
Water (%)	60 ± 0.2	60 ± 0.2	60 ± 0.2	59
Yeast (%)	–	–	4	4
Salt (%)	–	2	2	2
Chia (%)	1–3	1–3	1–3	1–3

Table 2 Chia gel formulation and nomenclature for the experiments (1). Results of the Farinograph measurements (2), of the max. force (N) and extensibility E (mm) measured by the Kieffer dough and gluten extensibility rig (3), the gaseous release time (min) and the dough height (mm) of the Rheofermentometer (4), of storage G' and loss G'' modulus of the frequency sweep measurements at 1 Hz frequency (5), the theoretical dough yields of all performed experiments (6) and the volume yield (mL/100 g flour) of the baking experiments (7)

		wd	*wd1c5w*	*wd2c5w*	*wd3c5w*	*wd1c10w*
1	Chia (%)	0	1	2	3	1
	Water (g/g_{Chia})	0	5	5	5	10
2	Water absorption (%)[a]	60.3 ± 1	58.8 ± 1	56.9 ± 1	55.5 ± 1	56.2 ± 1
	DDT (min)	2.4 ± 1	1.6 ± 1	2.4 ± 1	2.6 ± 1	2.1 ± 1
3	R_{max} (N)	0.41 ± 0.2	0.28 ± 0.1	0.17 ± 0.1	0.08 ± 0.1	0.13 ± 0.1
	E (mm)	44.84 ± 8	48.51 ± 1	52.51 ± 8	35.80 ± 2	45.76 ± 3
4	Dough height (mm)	37.2 ± 4	40.5 ± 4	44.7 ± 3	45.1 ± 2	44.7 ± 3
	Gaseous release time (min)	51.0 ± 3	60.3 ± 4	56.0 ± 5	64.3 ± 10	60.3 ± 6
5	log G′ (Pa)	9.3 ± 0.1	8.9 ± 0.1	8.6 ± 0.1	8.4 ± 0.1	8.6 ± 0.1
	log G″ (Pa)	8.5 ± 0.1	8.2 ± 0.1	7.9 ± 0.1	7.7 ± 0.1	7.9 ± 0.1
6	Dough yield[b] $_{theoretical}$	159c	165	170	175	170
7	Volume yield (mL/100 g flour)	473 ± 6.5	509 ± 3.3	588 ± 9.1	390 ± 18	580 ± 1

[a] water absorptions with the doughs containing chia gels are the proposal of the Farinograph. [b]Dough yield is a criterion for the ratio of water and flour in the dough. The theoretical dough yield refers to the water added by the chia gel. [c]Real dough yield, just water and flour, typical ratio for bread rolls and wheat bread

pectin (D-galacturonic acid) uronic acids are commonly used as gelling agents in food technology. The water-holding capacity of 15.41 g/g and the water absorption capacity (11.73 g/g) of chia fibre suggested a use as hydrocolloid [6]. Ground chia seeds added to oat products affect also pasting properties [11], it is assumed that it will also affect pasting properties of wheat starch. Different studies confirmed that hydrocolloids affect the rheology of bread doughs [12, 13] and could also be used as bread improvers and antistaling agents [14]. Ground chia is recently used as additive to bakery products like pound cake and gluten-free bread [15, 16]. Since 2013 the EU allows adding up to 10 % chia seed in baked products [17].

The aim of this study was to evaluate the technological effect of gel from ground chia for wheat dough processing and its influence on the shelf life of wheat breads. As discussed above, chia has high water absorption and holding capacity. To avoid competition of starch and ground chia, chia gel was incorporated as gel. The amount of water (5 on 1) for gel preparation was chosen to get a gel with a good stability based on the results of Inglett et al. [11]. The variation with water to chia 10 on 1 was performed to find out to what extent the gel composition affects doughs.

Materials and methods

Materials

Chia seeds (Hanoju, Germany) were milled with a centrifugal mill (ZM 100, Retsch Technology GmbH, Düsseldorf, Germany) to get ground chia. The ground chia was mixed with 5 g/g and 10 g/g water, respectively, and the mixture was stored for 10 min. The experiments (see Table 1 for various recipes) were carried out with commercial wheat flour (type 550: 0.51–0.63 % mineral supplements in dry matter, 13.17 or 12.8 % moisture content, Rettenmeier GmbH und Co. KG, Horb a.N., Germany), water, commercial yeast (Omas Ur Hefe, Fala GmbH, Bühl, Germany) and salt (Südsalz GmbH, Heilbronn, Germany). Sodium propionate 99 % (E281, Alfa Aesar GmbH & Co. KG, Karlsruhe, Germany) was used to avoid moulding of the bread loafs during storage. Chia gel formulations and nomenclature are shown in Table 2.

As specified by the manufacturer, chia seeds used for the experiments contain 31.4 g lipids, thereof 30.36 g omega-3-fatty acids, and 33.7 g/100 g total dietary fibre (TDF), which is in the range described by further research publications, the ratio of soluble/insoluble fibre is 1:7.

Methods

Dough characteristics

To determine the water absorption and the dough development time for 500 BU, Farinograph measurements of wheat flour were performed using the AACC method 54–21 [18]. The method was modified to a temperature of 32 ± 0.02 °C. The recipes for the following Farinograph measurements are described in Table 1. Threefold determinations were performed.

A Kieffer dough and gluten extensibility rig (Stable Microsystems, Surrey, UK) was used to obtain information of the maximum resistance (R_{max}) and the extensibility (Ext) following the described method of Kieffer et al. [19]. They found good correlations of rheological properties of dough and loaf volumes when doughs for extension and baking tests are produced under same conditions (temperature, composition, treatment; Kieffer et al. [19]). For this purpose, dough was prepared with a mini-Farinograph kneader (self-constructed kneader using a Brabender 50 g kneading cell without force absorption) with the same dough development time as determined for wheat flour. Doughs were prepared like the formula shown in Table 1. Threefold determinations were performed.

Dough proofing characteristics were determined using a Rheofermentometer F3 (Chopin, Villeneuve-la-Garenne Cedex, France). All measurements were taken in triplicate, and the average result is presented. The doughs (Table 1) were prepared in the Farinograph kneader. Gas production and dough height were measured with a charge of 1000 g over a 1.5 h period. Fundamental rheological characteristics were obtained on a rotational rheometer (Bohlin Rheometer CS, Lund, Sweden) using a parallel plate geometry (40 mm diameter). The dough samples (around 8 g) were loaded between the plates and pressed down to a final gap of 4 mm. To avoid the dough from drying out, the edges were coated with paraffin oil. Before the frequency sweep (0.01–10 Hz frequency, 0.001 deformation) measurement, the dough rests 10 min between the plates.

Rapid Visco Analyser (RVA-4 Stand alone, Newport Scientific, Australia) measurements were taken to obtain the pasting curves. The experiments were carried out as described in ICC Standard 162 [20]. Chia gel was added as in prior described experiments, but also with 5 and 15 % chia as gel, so that the influence of more added chia could be observed. Threefold determinations were performed.

Baking experiments

The doughs were prepared according to the dough formula described in Table 1 in a mixer (Diosna laboratory kneaders with group controller, Multimixing S.A. GmbH, Osnabrück, Germany) for 1 min at 25 Hz and for 5 min at 50 Hz. To avoid moulding, 0.27 % sodium propionate was added. The dough rested for 15 min at 32 °C and relative moisture of 80 % in a proofing chamber (Wachtel Stamm Petit Computer Proofing Chamber, Wachtel GmbH & Co., Hilden, Germany). Subsequently to the resting phase, the dough was separated into three equally weighted doughs and hand rounded. The dough rested for another 10 min, covered with a bowl at room temperature. The dough balls were long moulded, placed in loaf moulds, proofed in the proofing chamber for 40 min and baked in a deck oven (Piccolo I, Wachtel GmbH & Co., Hilden, Germany) for 35 min at 240 °C decreasing to 225 °C. Each experiment was carried out in duplicate.

Evaluation methods for the baking experiments

To evaluate the baking experiments, measurements were taken after 4 h of cooling to room temperature and after 24, 48, 72, 96 and 168 h of storage in plastic bags at 28 °C. The baking loss and volume yield were evaluated only after 4 h cooling period determined according to AACC Method 10–05 [18] rapeseed procedure, based on a volume displacement system.

Differential scanning calorimetry (DS C) was performed using a Perkin Elmer DSC 6 calorimeter. 0.25–0.5 g bread crumb was weighted into 40-μL sample pans (wall thickness 15 μm) and hermetically sealed with a cover. The reference pan was empty. The measurement is taken with a heating rate of 10 °C/min from 25 to 90 °C; each sample was measured five times. The raw data were analysed with the provided software (Perkin Elmer DSC 6 version 1.01, 1994, Perkin Elmer, Massachusetts, USA) to obtain the energy difference between the sample and reference pan, which is the gelatinization enthalpy ΔQ (J/g) in Joule per dry weight.

A texture analyser (TA-XT2, Stable Micro Systems, Surrey, England) was used with a modified AACC Method (74-09) for texture profile analysis (TPA). Three slices (25 mm thickness) were taken from the centre of the bread loafs. A standard 25 mm diameter probe and 5 kg load cell were used as measurement geometry. The bread slice was unlike the standard method penetrated up to 80 % deformation. The bread crumb firmness was the force measured at 40 % deformation.

Statistical analysis

The statistical analysis was carried out using MATLAB (version R2012b, 8.0.0.783). A one-way ANOVA was performed to determine whether there are significant differences between the experiments. The results of the measurements are compared within and between the groups. A 95 % confidence interval ($\alpha = 0.05$) is applied and provides the F test value, the number of measurements and different experiments specify the degree of freedom. If the obtained significance level (p value) is smaller than $\alpha = 0.05$, it is suggested that there exist more differences between as inside the group. If the significance level is $*p < 0.05$, there are more differences between as inside the tested groups.

Results and discussion

Effect of chia gel addition on dough rheology

In Table 2, (2) the results of the Farinograph measurements are presented. The added chia gel affects the time to reach the maximum dough consistency. The consistency of 500 BU is not reached within these experiments since the chia gel was added without correcting the water absorption, the same amount of water (determined by Farinograph measurements at the beginning only for wheat flour = 60.3 ± 0.2 %) was applied. The Farinograph proposed water absorptions for dough containing chia gels as presented in Table 2 (1). There is a correlation ($R^2 = 0.96$) of additional water and the correction proposal of the Farinograph visible. The dough development time (DDT) shows no significant difference, except *wd1c5w*, where it decreased.

It is also visible that after 9 min, there is an increasing on dough consistency in doughs with added chia gel shown in Fig. 1 by a vertical line. Lin et al. [10] described the main swelling fraction as a linear tetrasaccharide that incorporates structural features. It emerges in the mucilaginous gel when the seeds are soaked in water. That can act as a gum, which is described to absorb additional water as described by Upadhyay et al. [12]. Probably, the chia gel takes up further water or wheat proteins incorporated it due to a delayed swelling, which leads to an increasing consistency. An increasing of dough consistency was also observed by Bean et al. [21]. Weipert explained this due to a delayed swelling of wheat flour proteins [22]. Rosell et al. [13] studied the influence of hydrocolloids like Alginate, κ-Carrageenan, Xanthan and HPMC (Hydroxypropyl methylcellulose) on bread dough. Added chia gel behaves regarding the DDT similar to HPMC, since it does not affect this parameter that much. The amount of added chia flour is more than twice as much as the added HPMC; the water absorption of the measured doughs is not comparable

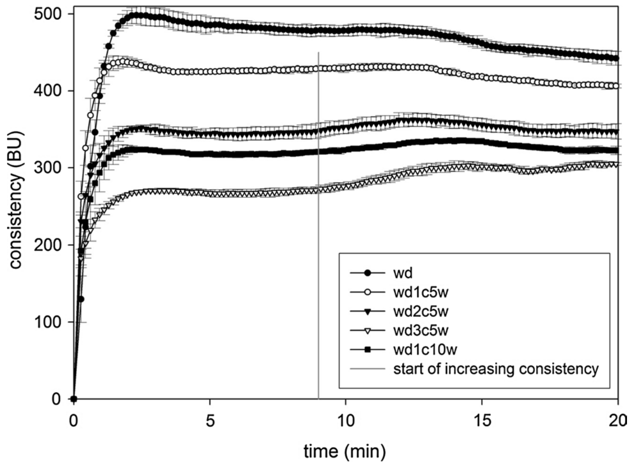

Fig. 1 Mean Farinograph curves of wheat doughs with their standard deviations

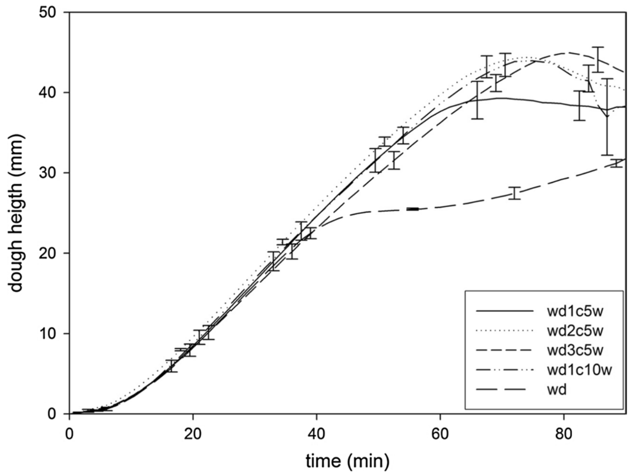

Fig. 2 Mean dough heights of the Rheofermentometer measurements during 90 min of fermentation and their standard deviations

with literature values since the proposed water absorptions proposed by the Farinograph have not been verified during this study. Another study that incorporated chia in wheat dough just added 5 % whole chia flour (equal to ground chia) and corrected the water absorption to 500 BU, but there was no significant difference [23].

In Table 2 (3) the results of the Kieffer dough and gluten extensibility rig measurements are presented. Mis and Dziki characterized the impact of dietary fibre on wheat dough [24] and observed an increased maximum resistance and decreased extensibilities. As it is observed reverse by our experiments, the water addition counteracts the effect of the addition of dietary fibre like ground chia.

The amount of added water leads to softer doughs, which show lower firmness and higher extensibility as described by Jekle and Becker [25]. Similar to these results are the ones of the Rheofermentometer. In Table 2 (4) the results of the maximum dough height and the gaseous release time of the Rheofermentometer measurements are presented. There is no significant difference in the gaseous release time with different amounts of chia, but the standard dough *wd* has a smaller gaseous release time value. The dough samples with chia gel have an increased dough height, which is also visible in Fig. 2. The evolution of the curves of the samples with added chia until 40 min is similar to dough without chia reaching its maximum after 40 min, indicating an invariant CO_2 production rate regardless the chia gel concentration.

A possible explanation for the increased dough height could be as proposed by Upadhyay et al. [12] that hydrocolloids form an additional layer of molecules around the bubbles in dough. Cui [26] figured out that polysaccharide gums increase the viscosity of the liquid medium of foams, which slows gas diffusion and stabilizes the film surrounding the gas bubbles. Considering dough as foam, the mucilaginous hydrocolloids stabilize the gas bubbles during fermentation.

The results of the storage G′ and loss G″ modules of the frequency sweep measurements at 1 Hz frequency are presented in Table 2 (5). The storage as well as the loss module decrease with the amount of chia gel added. Higher values for both modules with increasing frequency can be observed for all samples. This is also in accordance with studies performed by Inglett et al. [11] and Moreira et al. [16], presenting frequency sweep measurements with added chia to different grain products. The samples *wd2c5w* (square) and *wd1c10w* (rectangle) behave similar to each other; the other doughs are significantly different from each other. *wd3c5w* shows the smallest values for both modules. The increased water content with incorporated chia gel leads to decreased G′ and G″ as also noticed by Upadhyay et al. [12]. They described a reduction in dough firmness and elasticity, as also observed with the realized experiments for this study.

The dough samples *wd2c5w* and *wd1c10w* behave in different experiments similar to each other. This could be explained by the same amount of additional water (Table 2 (6), theoretical dough yields). Dough samples *wd3c5w* have a smaller maximum resistance and the lowest consistency in the Farinograph measurements, but regarding the results of the Rheofermentometer, there is no difference between the samples with other chia contents.

Effect of chia gel addition on pasting properties of wheat flour

In Fig. 3, the mean pasting curves and standard deviations of the RVA measurements are presented. With increasing chia concentration, the viscosity of all four wheat flour-chia suspensions is increased compared to the wheat flour suspension. The maximum of the viscosity peak changes with increasing chia gel content. The higher maximum viscosity and end viscosity indicate a higher water-holding capacity and ability to form a viscous gel after cooling, which should correlate with the end product quality. As there was a significant difference ($p = 0.0005$) between the experiments by adding 5 % chia, we additionally studied the influence of an increased chia content (15 %). The end viscosity is nearly reduplicated by increasing the chia content fivefold. Bárcenas et al. [27] reported that different levels of added hydrocolloids influence the pasting properties of wheat starch, but not in the dimension observed by addition of gel from ground chia.

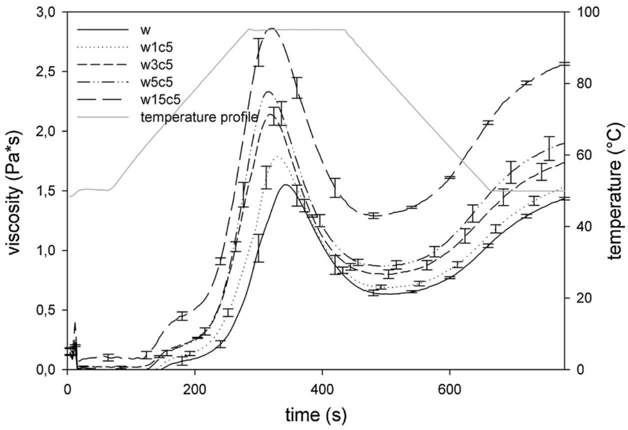

Fig. 3 Mean curves of the RVA measurements of wheat flour suspensions w with added chia gel 1 % (*w1c5*), 3 % (*w3c5*), 5 % (*w5c5*) and 15 % (*w15c5*) and their standard deviations. Development of viscosity over the time, right vertical axis shows the temperature profile

Effect of chia gel addition on bread quality and staling

Baking losses of the baking experiments were located in common range between 11 and 14 %. As the baking loss of all breads is in common range, the additional water contributed by the chia gel remains during baking in the breads. Theoretical dough yields and volume yields are presented in Table 2 (6 and 7). The dough yields as well as the volume yields suggested that the experiments *wd2c5w* and *wd1c10w* behave similar, because of the same amount of added water. The incorporated gel from ground chia increased the volume yields of all breads except *wd3c5w*. The volume of the breads increased up to 24 %, incorporation of 5 % ground chia leads to 14 % higher volumes [23].

DSC and TPA measurements are indicators for the staling of bread. Using DSC, structural properties can be analysed, whereas TPA gives macroscopic properties [28]. Due to the recrystallization of the starch granules, bread crumb

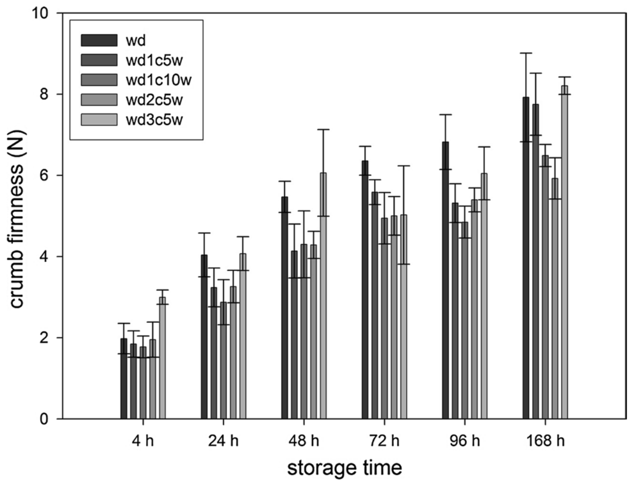

Fig. 4 Mean results of the bread crumb firmness of all breads over the storage period obtained by texture profile analysis. The error indicator bars are describing the respective standard deviation within the corresponding group

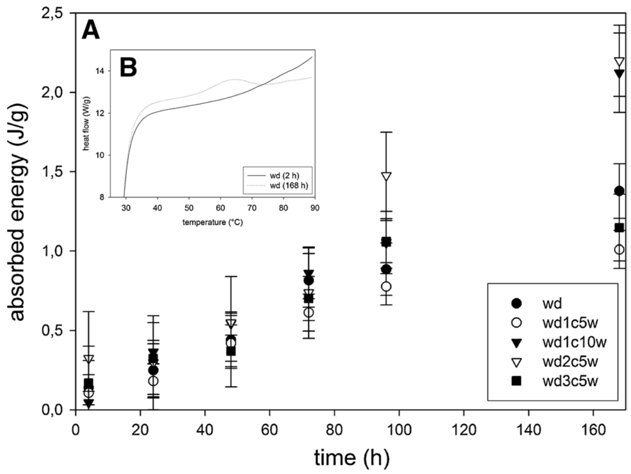

Fig. 5 Mean results and standard deviations of the DSC measurements (*A*) and exemplary DSC curves (*B*) for the standard wheat bread *wd*

firmness increases during storage period. The crumb firmness directly after cooling depends strongly on the density of the baked bread. A minor volume yield will result in a harder crumb. Most of the effects on crumb firming kinetics are due to the influence an additive has on the specific volume of breads [29]. In Fig. 4, the mean results and standard deviations of the bread crumb firmness during the storage period are presented. The results for the bread crumb firmness after 4 h are in accordance with volume yield presented in Table 2 (7). Regarding the standard *wd* and *wd3c5w,* no positive effect on staling can be recognized. This matches with the results of the Farinograph and Kieffer dough rig measurements. The measurements of the moisture content of the bread crumbs showed no significant differences between the breads over the time.

The results of the DSC measurements are presented in Fig. 5. The measured gelatinization enthalpy is higher after storage due to staling processes. Significant (*$p < 0.05$) differences can be seen after 96 h, due to the recrystallization of the starch granules, that happens in every bread sample. As expected the breads, *wd2c5w* and *wd1c10w* behave similar and significantly different to the other breads. The higher amount of absorbed energy is connected to a higher rate of staling due to the retrograded amylose and amylopectin and water migration from the crumb to the crust. One can see the increasing staling over the storage period. *wd1c5w* and *wd3c5w* show no significant effect on DSC measurements compared to the standard *wd*. As described by Atwell [30], DSC is the most chosen method to determine staling of bread by measuring the gelatinization enthalpy of starch. Since the breads with chia gel were significant softer in the TPA measurements except *wd3c5w* it could be assumed that staling increased there less. This assumption is rejected by DSC results, whereas the grade of staling needs not to be accompanied with an increase in crumb firmness, as described here. The addition of chia gel and incorporated water with a theoretical dough yield of 170 leads to a smaller amount of gelatinization during baking. Therefore, more crystallized starch is present in the samples after 168 h of storage. Beck et al. [31] found out that the retrogradation of starch is not a base for the rate of firming since there is a significant negative correlation between the two measurements ($r \geq -0.625$). The firming rate of wheat bread decreases also with additional water as described by Jekle and Becker [25].

The additional water incorporated with the chia gel provides longer water for the recrystallization of starch as also described by Rogers et al. [32], so the amount of absorbed energy increases longer for the samples *wd2c5w* and *wd1c10w*. Gray and Bemiller [33] concluded that amylopectin retrogradation plays a significant, but not the only, role in the staling process.

As discussed in chapter 3.1, the doughs *wd2c5w* and *wd1c10w* behave similar regarding the Rheofermentometer, Kieffer dough and gluten extensibility rig and rheometer measurements. It is assumed that this is caused by the same amount of additional water in the doughs. According to this study, chia is suitable for improving bread quality, as it behaves similar to HPMC, which was found suitable for improving bread quality [13]. Regarding the results of the baking experiments, it can be concluded that it is possible to produce adequate breads of doughs that have no consistency of 500 BU. The incorporation of dietary fibre is most commonly to prolong freshness of baked products for their capacity to retain water. The changes in appearance were fractional up to 2 % incorporated gel from ground chia.

Conclusion

Bread quality can be increased by adding chia gel, but only to a small extent. It has to be the right ratio of water and ground chia. 3 % ground chia mixed with 5 g/g water affects the dough negatively regarding volume yield of the baking experiments. An optimal dosage for wheat bread as presented in this study is 2 % ground chia mixed with 5 g/g water or 1 % ground chia mixed with 10 g/g water as it affects the volume yield and softness of the bread crumb in a positive way. Breads with added chia have a higher nutritional value and could be used as functional food. The processability of wheat dough with added chia gel depends on the amount of added chia gel, because the dough softness and stickiness increases with increasing gel and therefore water content. This is also reported for incorporation of dietary fibre in baked products [8]. Further experiments could examine the effect of adding dry or hydrated hydrocolloid, as in this study, hydrated ground chia was applied to avoid competition of both hydrocolloids.

Conflict of interest None.

Compliance with Ethics Requirements This article does not contain any studies with human or animal subjects.

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3.2 Chia (*Salvia hispanica* L.) as fat replacer in sweet pan breads

The effects of gel from ground chia (Salvia hispanica L.) were studied as a fat replacer in sweet pan breads. This substitution was addressed to reduce the total amount of fat in the product and to improve the nutritional value of the products regarding the fatty acid composition. The effects on the baking results were determined by assessing common baking evaluations and texture analysis after 2 h and 48 h.

The doughs were characterised with rheometer and Rheofermentometer measurements. Rheometer measurements revealed that the replacement resulted in softer doughs with decreasing values for storage and loss moduli with increasing chia content. The yeast activity was increased with incorporated chia gel compared to the control. The best results for the baking experiments were obtained with 25 % fat replacement through ground chia gel. Here, the highest volume yield with the softest crumb even after 48 h was achieved.

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Original article

Chia (*Salvia hispanica* L.) as fat replacer in sweet pan breads

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Summary The effects of gel from ground chia (*Salvia hispanica* L.) were studied as a fat replacer in sweet pan breads. This substitution was addressed to reduce the total amount of fat in the product and to improve the nutritional value of the products regarding the fatty acid composition. The effects on the baking results were determined by assessing common baking evaluations and texture analysis after 2 and 48 h. The doughs were characterised with rheometer and rheofermentometer measurements. Rheometer measurements revealed that the replacement resulted in softer doughs with decreasing values for storage and loss moduli with increasing chia content. The yeast activity was increased with incorporated chia gel compared to the control. The best results for the baking experiments were obtained with 25% fat replacement through ground chia gel. Here, the highest volume yield with the softest crumb even after 48 h was achieved.

Keywords Baking, dietary fibre, dough, fatty acids, functional foods, omega 3, rheology, texture profile analysis.

Introduction

Consumers' demand for good-tasting sweet bakery products with high nutritional values. Sweet pan breads contain more than 10% fat and sugar with respect to the flour mass. Fat is important for sensory attributes such as texture, elasticity, flavour and dough handling of baked goods (Lucca & Tepper, 1994). Affecting the structure, air is trapped by fat during the creaming process and baking (Giese, 1996), as fat crystals melt and thereby make it possible for the crystal–liquid interface to be incorporated into the surface of the bubble as it expands (Brooker, 1996).

Bakery products containing high amounts of fat can be modified in two ways: fat reduction and improving the quality of the used fat. There are diverse fat replacers used in food production. They can be separated in protein-, carbohydrate- and fat-based. Carbohydrate fat mimetics for example stabilise substantial quantities of water and form gels (Lucca & Tepper, 1994) like cellulose or plant gums. Cellulose ethers were recently evaluated as fat replacers in bakery products (Martínez-Cervera *et al.*, 2015; Sanz *et al.*, 2015). The effect of fat reduction on sweet bread was evaluated by Calligaris *et al.* (Calligaris *et al.*, 2013). They used monoglyceride organogel containing sunflower oil (a fat-based mimetic) and obtained baking results comparable to their control sample prepared with palm oil.

Chia (*Salvia hispanica* L.) is a subtropical annual plant belonging to the *Lamiaceae* family. Chia seeds are nutritionally valuable (Ixtaina *et al.*, 2008; Ayerza & Coates, 2011). Depending on cultivar and growth conditions, they contain about 30 g/100 g fat, with high amounts of linolenic (about 60%) and linoleic (about 20%) acids (Taga *et al.*, 1984; Ayerza, 1995; Vázquez-Ovando *et al.*, 2009) depending on cultivar and growing conditions.

Besides the valuable fatty acid composition of chia seeds, their content of dietary fibre TDF is between 18 and 60 g/100 g (Reyes-Caudillo *et al.*, 2008), which include polysaccharides, oligosaccharides, lignin and other associated substances. The incorporation of dietary fibre is most commonly used to prolong freshness of baked products for their capacity to retain water. The main challenge of additional fibre in cereal products is the adverse effect on the end product quality (Foschia *et al.*, 2013). Lin *et al.* (Lin *et al.*, 1994) determined within the chia gel mucilage, a linear tetrasaccharide that contains 25% uronic acid. Like pectin (D-galacturonic acid), uronic acids are commonly used as gelling agents in food technology. The water holding capacity of 15.41 g g^{-1} and the water absorption capacity (11.73 g g^{-1}) of chia fibre suggested a use as hydrocolloid (Vázquez-Ovando *et al.*, 2009). Capitani *et al.* (2015) presented the application of chia as food additive to obtain certain rheological behaviours.

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To improve the quality of fat in bakery products, different authors used chia. Borneo *et al.* (2010) used chia gel as egg or oil replacer in cake formulations and achieved good baking results by a substitution of 25%. Here, the cakes were not significantly different from the control for colour, taste, texture and overall acceptability. The improvement of pound cakes with whole chia flour and hydrogenated vegetable fat was investigated by Luna Pizarro *et al.* (2013), and according to them, the optimal chia cake presented a significant increase in the protein (7 g/100 g), lipids (31 g/100 g) and ash (19 g/100 g) contents as compared to the control cake.

In pound cakes, 25% of fat can be replaced by chia mucilage gel without significant alterations on their quality characteristics (Felisberto *et al.*, 2015). Most studies reported a negative effect on the colour of the crumbs. Concerning this matter, Baixauli *et al.* (2008) investigated the increasing consumer acceptability of muffins, when information about the new ingredient, for example fibre, is provided. In summary, Chia is recommended as ingredient for bakery products by several authors. Sweet pan bread is leavened yeast dough and therefore basis for many sweet snacks and viennoiserie. The evaluation of this dough may help to invent sweet snacks (based on sweet yeast dough) with improved nutritional values. According to the guidelines for fine bakery products (German Food Code Commission (DLMBK)) and subsequently for the preparation of sweet yeast dough, no special fat is required. The guidelines prescribe that the amount of sugar and or fat has to be more than 10–90 parts of cereal flour products.

The purpose of this study was to prepare sweet pan bread with chia as partial fat replacer, to obtain a better fatty acid profile resulting in a higher nutritional value for these sweet baked goods. The effects of the incorporated ground chia were investigated regarding the baking results, shelf life and fatty acid composition for the most promising sample. The fat was replaced in four steps, and the ratio among the ingredients was held constant, so that every bread had the same dough mass.

Table 1 Recipes for the sweet pan doughs and the variation of recipes regarding the amount of added fat

	STD	C1	C2	C3	C4
Flour [g/100 g flour]	100	100	100	100	100
Fat [g/100 g flour]	20	15	10	5	0
Chia [g/100 g flour]	0	5	10	15	20
Water [g/100 g flour]	44	69	94	119	144
Sugar [g/100 g flour]	15	15	15	15	15
Whole egg [g/100 g flour]	7	7	7	7	7
Whole milk powder [g/100 g flour]	6	6	6	6	6
Salt [g/100 g flour]	1.5	1.5	1.5	1.5	1.5
Yeast [g/100 g flour]	1.25	1.25	1.25	1.25	1.25
Amount of fat replacement [%]	0	25	50	75	100
Added amount of chia [%] calculated	0.00	2.33	4.20	5.77	7.03
Added amount of fat [%] calculated	10.41	7.06	4.33	2.10	0.21

Materials and methods

Ground chia seeds were kindly donated by Chiabia Germany (Schenefeld). As specified by the manufacturer, chia seeds used for the experiments contain 31 g lipids, thereof 24 g omega-3 fatty acids and 33 g total dietary fibre (TDF) in 100 g. The experiments (see Table 1) were carried out with commercial wheat flour (type 550: 0.51–0.63% mineral supplements in dry matter, Rettenmeier GmbH und Co. KG, Horb am Neckar, Germany). Further ingredients were as follows: palm fat (Daabon Organic Japan Co. Ltd, Tokyo, Japan), water, dry yeast (saf-instant, S.I. Lesaffre, Marcq, France), salt (Südsalz GmbH, Heilbronn, Germany), sugar (Südzucker Group, Mannheim, Germany), whole liquid pasteurised eggs (Eipro-Vermarktung GmbH & Co. KG, Lohne, Germany) and whole milk powder (J.M. Gabler Saliter, Obergünzburg, Germany). Palm fat was used here to show how effective the fat replacement with gel from ground chia can be. Palm fat is commonly used in food applications (85% of palm oil are used for food), because of its heat stability and cost efficiency (May & Nesaretnam, 2014).

All doughs were prepared in a planetary mixer (N50, Hobart GmbH, Offenburg, Germany) according to Table 1. For every experiment, 500 g of dough was prepared. Fat was replaced in 25% steps up to 100% fat replacement by chia gel as presented in Table 1. C1 was then 25% of the fat that was replaced by chia gel for example. Measurements were made in triplicate for the standard, C1 and C2, where each dough was separately mixed and the average result is presented. Doughs for recipes C3 and C4 were produced and baked only one time and rejected because of their appearance. Ingredients for the predough and main dough are summed up. The amounts of chia and fat are calculated regarding the dough. The amount of fat in additional ingredients is unattended as there were no changes.

The doughs for the sweet pan breads were prepared with a sponge dough. The water content for the dough was defined of the used recipe. For the predough, a dough yield of 160 was chosen, for the main dough, a dough yield of 144 was set (defined of the chosen recipe). Less water is required in doughs with high sugar and/or fat contents. The sponge dough was mixed for 30 s at level 1 and kneaded for 1 min at level 2. The mixing time was chosen according to pre-experiments to obtain a good kneaded homogenous dough. The dough rested for 30 min at 30 °C and 80% relative moisture in a proofing chamber (Wachtel Stamm Petit Computer Proofing Chamber, Wachtel GmbH & Co., Hilden, Germany). Meanwhile, ground chia was mixed with 5 g water per g chia, and the mixture was stored for 10 min. After the dough rest, the additional ingredients were added to the sponge dough, mixed for 30 s at level 1 (139 r.p.m.) and kneaded for 1 min at level 2 (285 r.p.m.).

Dough characteristics

Dough proofing characteristics of the sweet pan breads were determined using a rheofermentometer F3 (Chopin, Villeneuve-la-Garenne Cedex, France). For this, 200 g of dough was separated and put into the fermentation chamber after the kneading. Gas production and dough height were measured with a load of 1 kg over a 1.5-h period.

Effects of incorporating chia to the doughs were evaluated through rheological measurements. Fundamental rheological characteristics of the doughs were obtained using a rotational rheometer (MCR 302; Anton Paar, Graz, Austria) with a parallel plate geometry (25 mm diameter). The samples were loaded between the plates and pressed down to a final gap of 2 mm. To avoid the dough from drying out, the edges were coated with paraffin oil and covered. To determine the linear-viscoelastic region, amplitude sweep tests were performed (0.001 to 100% deformation at 10 rad s^{-1}). The obtained data of the performed frequency sweep (100 to 0.1 1 per s within the LVE region, $\gamma = 0.05\%$) test for the storage G' and loss G'' moduli were fitted to the following equations, according to Moreira *et al.* (2013). The used fitting parameters are p_1 to p_4.

$$\log G' = \log(p_1) + p_2 * \log(\omega) \quad (1)$$

$$\log G'' = \log(p_3) + p_4 * \log(\omega) \quad (2)$$

Immediately after the frequency sweep tests, creep recovery tests were performed. The creep phase ($\tau = 50$ Pa for 5 min, 91 measuring points, duration 0.01- to 25-s log) and the recovery phase (10 min, 185 measuring points, duration 0.01- to 25-s log) were individual fitted to the extended Burger model (eqn 3) which consisted of one Maxwell and three Kelvin–Voigt modules all in series.

$$J(t)_{\text{creep}} = J_0 + \frac{(t-t_0)}{\eta_0} + J_1 * \left(1 - e^{-\frac{(t-t_0)}{\lambda_1}}\right) + J_2 * \left(1 - e^{-\frac{(t-t_0)}{\lambda_2}}\right) + J_3 * \left(1 - e^{-\frac{(t-t_0)}{\lambda_3}}\right) \quad (3)$$

Here, J_1 to J_3 are the viscoelastic compliances, λ_1 to λ_3 are the corresponding retardation times, t is the measuring time. The evaluation of the zero viscosity η_0 (flowability of the material at the end of applied load) and creep compliance J_0 (instantaneous deformation) was done with the creep regression analysis included in RHEOPLUS/32 V3.62 (Anton Paar).

Baking experiments

After kneading, the dough rested for 15 min at 30 °C and relative moisture of 80% in a proofing chamber (Wachtel Stamm Petit Computer Proofing Chamber, Wachtel GmbH & Co.). Subsequently to the resting phase, the dough was separated into two equally weighted doughs and hand rounded. The dough rested for another 10 min and covered with a bowl at room temperature. The dough balls were long moulded, placed in loaf moulds, proofed in the proofing chamber for 60 min and baked in a deck oven (Piccolo I, Wachtel GmbH & Co.) for 20 min at 200 °C with 12-s vapour at the beginning. Some doughs (C3 and C4) were very soft and slippery, so they were placed in the baking moulds after the dough rests directly.

Evaluation of the baking experiments

To evaluate the baking experiments, measurements were carried out after 2 h of cooling at room temperature and after 48 h of storage in plastic bags at 28 °C. The baking loss, the volume and the crumb colour were evaluated only after 2-h cooling period. The volume was determined with a volume scanner (Volscan profiler 600; Stable Micro Systems, Surrey, England). The baking loss is the mass difference of dough and bread divided by the mass of the bread.

A texture analyser (TA-XT2; Stable Micro Systems) was used with a modified AACC method (74-09) for texture profile analysis (TPA). Three slices (25 mm thickness) were taken from the centre of the sweet pan bread loafs. A standard 25-mm-diameter probe and 5-kg load cell were used as measurement geometry. The three bread slices were two times compressed up to 40% deformation with 15-s rest, and the test speed was 1.7 mm s^{-1}. The bread crumb firmness and the elasticity were evaluated.

For three samples, the standard, C1 and ground chia seeds, the raw fat and the fatty acid distribution was evaluated by the State Institute for Agricultural Chemistry (accredited testing institute DIN EN ISO/IEC 17025:2005, Stuttgart, Germany). The fatty acid profile was determined according to their method (SOP P23-5-008), where the fatty acid methyl esters of fat for the quantitative GC-determination of the total fat spectrum are expressed as the weight of the residue as a percentage of the sample. The standard used was Supelco 37-Component FAME Mix (Supelco, Bellefonte, PA, USA), and the used column was a Agilent J&W GC Column Catalog 122-2332 DB – 23 (length

30 m × 0.25 mm × 0.25 μm). The fatty acid profile was evaluated for the standard recipe (STD), the highest amount of incorporated chia with the best baking result and the ground chia alone in duplicate. The raw fat was determined according to procedure B of the determination of crude oils and fats of the Commission Regulation (EC) No 152/2009 III H (European Commission, 2009).

Statistical analysis and curve fitting

The statistical analysis and curve fitting were carried out using MATLAB (version R2014b, 8.4.0.150421). A one-way ANOVA was performed to determine whether there are significant differences between the experiments. The results of the measurements are compared within and between the groups. A 95% confidence interval ($\alpha = 0.05$) is applied and provides the *F*-test value, and the number of measurements and different experiments specify the degree of freedom. If the significance level is $*P < 0.05$, there are more differences between as inside the tested groups. In this case, the multiple comparison test (default: Tukey–Kramer test) implemented in MATLAB statistical toolbox was used to determine statistical differences between means. Significant differences are indicated with different letters within one row.

Results and discussion

Effect of chia addition on dough characteristics

The doughs obtained with recipes C3 and C4 were highly fluid, and the baking results were not satisfying; therefore, no dough evaluation was performed.

The results of the rheofermentometer measurements are presented in Fig. 1 for the dough development curve and in Table 2 for the gaseous release curve. The dough samples with chia gel have an increased dough height (Fig. 1) and a higher maximum slope 0.6 vs. 0.4 mm min^{-1} indicating a higher CO_2 production rate compared to the standard. Subsequently, the time $T1$, when the maximum dough height is reached, decreases with increasing amount of added chia. As water is added to the dough, the higher amount of available water for the yeast may lead to this effect. A possible explanation for the increased maximum dough height Hm could be as proposed by Cui (2000). He figured out that polysaccharide gums increase the viscosity of the liquid medium of foams, which slows gas diffusion and stabilises the film surrounding the gas bubbles. Considering dough as foam, the mucilaginous hydrocolloids stabilise the gas bubbles during fermentation and therefore increase the stability of the doughs.

There is a significant difference in the gaseous release time Tx with chia (C1, C2) compared to the standard STD that has a higher gaseous release time value. The total volume of produced CO_2 indicates that the yeast cells in the doughs with incorporated chia produced a higher amount of CO_2. The maximum slope of the gaseous release is significantly higher for the doughs with chia as shown in Table 2. The formed protein network is obviously not able to retain the produced CO_2 for the whole measurement time. A possible explanation could be the higher tension on the dough surface because of the higher dough volume. According to that, the amount of retained carbon dioxide decreases with higher amounts of chia (compare the retention coefficients).

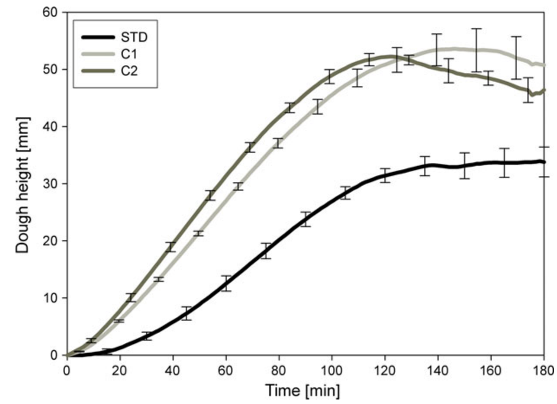

Figure 1 Mean values and standard deviations *(SD)* of the dough development curves measured with the rheofermentometer.

Table 2 Results of the rheofermentometer measurements

	STD	C1	C2
Dough development			
Hm [mm]	34 ± 2^{a}	54 ± 3^{b}	52 ± 1^{b}
*T*1 [min]	165 ± 20^{a}	$149 \pm 7^{a,b}$	123 ± 3^{b}
Max. slope of the dough development curves [mm/min]	0.4	0.6	0.6
Gazeous release			
H′m [mm]	34 ± 2^{a}	50 ± 0.3^{b}	57 ± 1^{c}
T′1 [min]	117 ± 10^{a}	114.0 ± 9^{a}	102 ± 2^{a}
Tx [min]	124 ± 5^{a}	100 ± 3^{b}	77 ± 7^{c}
Total volume [mL]	831 ± 44^{a}	1199 ± 4^{b}	1347 ± 18^{c}
Retention coefficient [%]	98 ± 5^{a}	94 ± 1^{b}	90 ± 1^{c}
Max. slope of the gaseous release curve [mm/min]	2.1 ± 0.1^{a}	3.2 ± 0.2^{b}	3.7 ± 0.3^{b}

Means followed by the same superscript lowercase letters in the same row did not differ ($P < 0.05$) by the Tukey test.

Summarising the higher maximum slope of the dough as well as the gaseous release curves indicates that less fat and more water promote the yeast activity.

The end of the linear-viscoelastic region (LVE) was found in all samples to be lower than 0.05% deformation (Fig. 2).

Frequency sweep measurements showed the predominance of the elastic properties of the viscoelastic dough. The storage and the loss moduli decrease with the amount of fat replaced by chia gel. Higher values for both modules with increasing frequency can be observed for all samples as presented in Fig. 3. At low frequencies, the time behaviour of the samples is observed, and the moduli approach each other with decreasing frequency. Subsequently, the loss factor tan δ indicates a shift from more elastic to viscous behaviour. This is also in accordance with studies performed by Inglett *et al.* (2014) and Moreira *et al.* (2013), presenting frequency sweep measurements with added chia to different grain products. C2 shows the smallest values for both moduli. The increased water content with incorporated chia gel leads to decreased G' and G'' as also noticed by Upadhyay *et al.* (2012). They described a reduction in dough firmness and elasticity, as also observed in this study. The doughs with replaced fat are more flexible towards stress, which leads also to a higher dough in the rheofermentometer and subsequently to higher volume yields in the baking experiments.

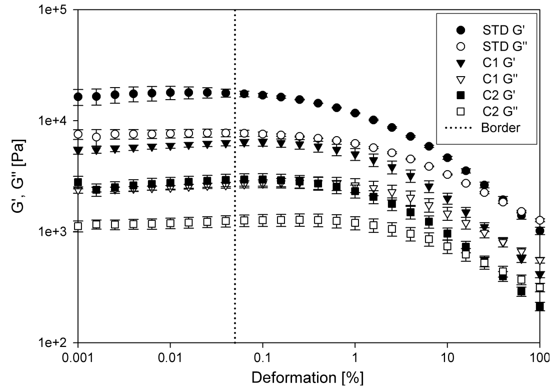

Figure 2 Results of the amplitude sweep measurements (mean values and *SD*) with the determined border of the LVE-limit.

The values for tan δ, the ratio between loss and storage modulus are affected with chia gel addition, but the tendencies remain the same. With increasing frequency, tan δ decreases, indicating the degree of viscous behaviour decreasing. Inglett *et al.* reported the same behaviour for oat bran concentrate (OBC) dry blended with ground chia seeds. They concluded that the enhanced elastic behaviour may be attributed to some components and structure of OBC and provides better shape retention during handling (Inglett *et al.*, 2014). The special composition (high amount of sugar and fat) of sweet pan dough, which is generally firmer, may explain this effect in this study.

The calculated values for p_1 to p_4 are presented in Table 3 (1). The coefficients of correlation indicate good correlations of the obtained data with the models.

The obtained values for p_1 and p_3 decrease significantly with the amount of added chia gel. Moreira *et al.* (2013) also reported this effect of adding chia and chia combined with different hydrocolloids on chestnut flour.

By the presence of added hydrocolloid, p_2 and p_4 are not affected. There is no trend visible regarding p_2

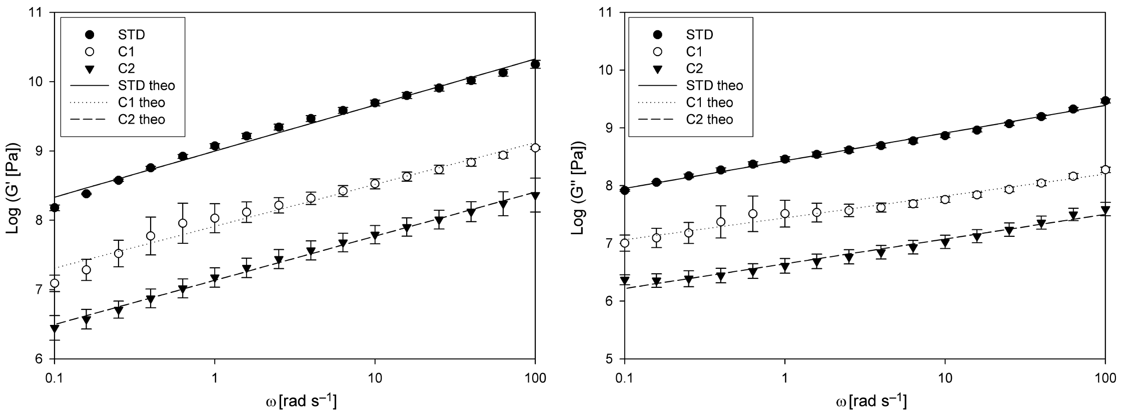

Figure 3 Mean values for storage (G′, left) and loss (G″, right) moduli with their corresponding model values obtained with eqns 1 and 2.

Table 3 Parameters of oscillatory shear modelling of storage G' and loss modulus G'' (1). Results of the creep recovery measurements (2)

Parameter			STD	C1	C2
1	G'	p_1 [Pa × s^{-p2}]	3131 ± 82^a	1261 ± 288^b	546 ± 53^c
		p_2 [−]	0.21 ± 0.01^a	0.17 ± 0.04^a	0.19 ± 0.01^a
		FQS	0.08 ± 0.03	0.2 ± 0.2	0.04 ± 0.01
		R^2	0.987 ± 0.005	0.954 ± 0.05	0.992 ± 0.002
	G''	p_3 [Pa × s^{-p4}]	4758 ± 36^a	1683 ± 331^b	754 ± 106^c
		p_4 [−]	0.29 ± 0.01^a	0.27 ± 0.03^a	0.28 ± 0.02^a
		FQS	0.02 ± 0.01	0.1 ± 0.13	0.09 ± 0.08
		R^2	0.993 ± 0.003	0.922 ± 0.105	0.964 ± 0.04
2	η_0 [10^3 Pa × s]		206 ± 9^a	83 ± 16^b	32 ± 6^c
	J_0 [10^{-3} 1 Pa^{-1}]		0.5 ± 0.1^a	1.5 ± 0.2^b	2.6 ± 0.3^c

Means followed by the same superscript lowercase letters in the same row did not differ ($P < 0.05$) by the Tukey test.

and p_4. Using an exponential equation, p_1 ($R^2 = 0.9994$) and p_3 ($R^2 = 0.9948$) can be correlated with the amount of chia. However, the number of measurement points is very low.

Creep recovery tests confirm earlier observations regarding the dough softness with chia gel as fat replacer. The results are presented in Table 3 (2). The values obtained by the rheometer evaluation method for the zero viscosity η_0 decrease exponential ($R^2 > 0.99$), and the ones for the creep compliance J_0 increase linear ($R^2 > 0.99$) with increasing chia gel content. These values were obtained by merely modelling the creep phase.

This is in accordance with different other studies on the influence of chia on dough systems (Moreira *et al.*, 2013) or the effect of increasing amounts of water on wheat dough (Mastromatteo *et al.*, 2013).

Summarised all dough characterisations confirm that the doughs chia gel, and therefore also water, as partial fat replacer leads to softer doughs. They seem to be more flexible towards stress, resulting in smaller values for storage and loss moduli as well as viscosities.

Effect of chia addition on the baking experiments

The results of the baking experiments are displayed in Table 4. The best baking results were obtained with 5 g chia (2.3% related to the dough mass) and 25 g additional water per 100 g flour (sample C1). Here, a good looking sweet pan bread resulted with high crumb elasticity and low crumb firmness. The baking loss increased with increasing gel and subsequently water content of the doughs. The volume yield [mL g_{flour}^{-1}] increased significantly (*$P < 0.05$) with incorporated chia gel. Similar results were achieved by Felisberto *et al.* (2015) and Borneo *et al.* (2010) when they replaced 25% fat in pound cakes with chia mucilage gel. On the contrary, Coelho and Mercedes (2015) observed decreasing specific volumes when they added chia to their bread, but they substituted partly the wheat flour.

As can be seen in Table 4, the crumb firmness decreased with incorporated chia gel as partial fat replacer 2 h after baking as well as 48 h. The crumb elasticity of the sweet pan breads with chia gel was slightly higher compared to the standard 2 h after baking. Forty-eight h after baking, the crumb elasticity of the standard bread was significantly lower compared to the breads with chia gel. The incorporated chia gel leads therefore to a longer freshness of the sweet pan breads regarding the texture.

The effect of chia addition on the crumb structure and volume of sweet pan breads is presented in Fig. 4. Increasing chia addition leads to darker crumbs and coarser pores. This may be caused by the fact that the

Table 4 Results of the baking experiments and the texture analysis: crumb firmness and crumb elasticity 2 and 48 h after baking. No standard deviations for C3 and C4 as they were baked only one time and rejected because of their appearance

		STD	C1	C2	C3	C4
Baking loss [%]		8.8 ± 0.4^a	12.1 ± 0.5^b	13.4 ± 0.4^c	14.5	16.1
Volume yield [mL/g flour]		4.7 ± 0.3^a	5.5 ± 0.2^b	5.7 ± 0.2^b	5.6	6.3
Specific volume [mL/g]		2.7 ± 0.2^a	2.9 ± 0.1^a	2.8 ± 0.1^a	2.5	2.6
Firmness [N]	2 h	5.4 ± 0.7^a	3.2 ± 0.5^b	3.4 ± 0.4^b	4.7	2.9
	48 h	15.4 ± 1.5^a	8.6 ± 0.4^b	8.8 ± 0.8^b	9.1	3.9
Elasticity [−]	2 h	0.9407 ± 0.0052^a	0.9690 ± 0.0025^b	0.9717 ± 0.0005^a	0.9690	0.9660
	48 h	0.8743 ± 0.0113^a	0.9303 ± 00021^b	0.9577 ± 0.0068^a	0.9590	0.9720

Means followed by the same superscript lowercase letters in the same row did not differ ($P < 0.05$) by the Tukey test.

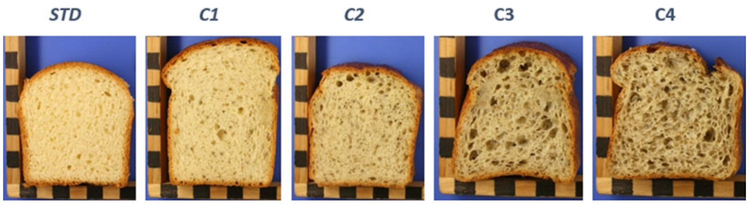

Figure 4 Crumbs of the prepared sweet pan breads.

doughs with 75% and 100% fat replacement could not be processed like the standard and were filled into the pans directly after the dough rest. Because of their appearance, these samples were only tested once.

Effect of chia addition on the fatty acid profile

As part of the used palm fat was replaced by ground chia, the fatty acid profile was changed in the expected way. The amount of myristic (around 1.6%) and stearic acid (around 5%) in the fatty acid spectre was not influenced by the fat replacement for both samples. As expected, the amount of palmitic and oleic acid was decreased (STD: 40.4%, C1: 35.4% and STD: 38.3%, C1: 35.8%, respectively), whereas the amount of linoleic and linolenic acid increased (13% and 5%) compared to the amounts of the spectre of the standard (12% and 0.5%). These fatty acid contents are related to the complete amount of fat, which was 2.75% lower in the recipe C1 with 2.3% chia. Ground chia seeds had a fat content of 32.2%. The amounts of linoleic and linolenic acid were 19.6% and 61.7%, respectively. Luna Pizarro *et al.* (2013) evaluated also the fatty acid profiles of pound cakes with 15 g chia and 20% hydrogenated vegetable fat per 100 g flour and observed also an increase in the amount of linoleic acid. In accordance with the presented results in this study, Coelho and Mercedes (2015) reported an increase in linoleic and linolenic acid by adding chia to wheat doughs. Mohd Ali *et al.* (2012) discussed the safety and efficiency of chia and concluded that although further studies are required, chia seed oil can maintain a balanced serum lipid profile. The nutritional quality of chia has been evaluated by Ayerza and Coates (2005, 2007). They feeded rats with chia seed and chia oil. The results show an increase in HDL cholesterol and ω-3 fatty acid contents, with a significant improvement in n-6/n-3 fatty acid ratio, in rat serum. They concluded that chia, rich in the essential α-linolenic acid, might be an alternative ω-3 source for vegetarians and people allergic to fish and fish products. The characterisation and comparison of the chemical composition of exotic superfoods concluded that already 10 g chia seeds would provide significant contribution to the diet in terms of inorganic nutrients (Llorent-Martínez *et al.*, 2013).

Conclusion

It is possible to replace fat with chia gel as presented in this study. The replacement leads to an improved product quality up to 50% fat replacement. Improved product quality here is referred to a prolonged freshness and higher volume yields. Higher fat replacements lead to doughs difficult to process and is not recommended. Doughs with incorporated chia gel are softer as confirmed also by different authors. This fact can be explained with the increased amount of water, resulting in higher elasticity of doughs and therefore more flexibility towards stress, higher growing rates of the dough and subsequently higher volume yields in the baking experiments. As the dough proofing time for the baking experiments was lower than the time of the gaseous release, this negative effect did not appear here. On the contrary, as the dough grows faster, the volume yields of the sweet pan breads with incorporated chia gel increased compared to the standard.

A small replacement of fat with chia gel leads therefore to a more nutritional valuable product with positive effects on the volume (Borneo *et al.*, 2010; Felisberto *et al.*, 2015). Using chia as fat replacer is also an important advantage for clean label products, because no other additives or ingredients are needed to reduce the amount of fat in sweet pan breads.

Acknowledgments

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3.3 Optimization of the production parameters for bread rolls with the Nelder-Mead simplex method

An efficient method for the optimization of processing parameters for bread rolls is presented with this contribution. The processing parameters for a new oven were needed. The walls of the oven were coated with a special ceramic, that increases the infrared radiation during the baking process. As a result the standard baking program lead to horrible baking results. Pre-experiments lead with same baking temperature and a time reduction of around 25 % to good baking results, compared to the ones baked in a conventional oven (Zettel *et al.*, 2016). The next step was to modify the proofing time, because the oven manufacturer proposed a prolonged proofing. The baking temperature and the proofing time were then the two optimization parameters, the baking time was fixed to 16 minutes. The Nelder-Mead simplex method was chosen, because it is well established in chemical processes, but not common in cereal technology. It is also known as straight forward method and the hope was to need only few experiments to obtain a good result.

The optimization lead within 11 experiments to an optimal proofing time of 117 minutes and a baking temperature of 215 °C. The publication has been submitted to a journal and is currently under review.

Optimization of the production parameters for bread rolls with the Nelder-Mead simplex method

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Abstract

In this contribution an efficient method for the optimization of processing parameters for bread rolls is presented. The optimization was carried out for a new oven type starting with the normal recipe for bread rolls. The new oven type was coated with a ceramic that increased the infrared radiation during the baking process. The baking process is therefore accelerated and the processing parameters had to be adjusted newly. The process parameters proofing time and the baking temperature were optimized. The quality criterion was defined by the characteristics of bread rolls obtained from the conventional oven using the specific volume, the baking loss, the colour saturation, crumb firmness as well as the elasticity. The Nelder-Mead simplex method led within 11 experiments to an optimal baking result. The optimization was terminated when the values for the confidence interval of the objective function include zero. The optimal processing parameters for the bread rolls were a proofing time for 117 minutes and the baking temperature of 215 °C for 16 minutes.

Keywords: proofing, baking, optimization, Nelder-Mead simplex method, infrared radiation

1. Introduction

During baking processes heat energy is transferred into baking products. This happens by conduction from the bottom of the oven, by convection through the air, condensation of steam and thermal radiation. Depending on the temperature of the emitter, principally heat radiation contains high amounts of infrared, but can also contain visible and even mostly tiny amounts of ultraviolet radiation intensity (Lerner, 1991; Lienhard, 2011; Smith, 2011). At typical baking temperatures around 200 °C (Gould, 2007), the thermal radiation consists mainly of infrared radiation. A piece of dough is absorbing, emitting and reflecting electromagnetic radiation (Lienhard, 2011; Krishnamurthy et al., 2008). The infrared radiation is said to penetrate the dough piece in a better way and heat it from the inside faster than in conventional radiation ovens. The penetration depth of near infrared radiation with a wavelength of 1 μm is about 4-6 mm (Pan and Atungulu, 2011). Purlis optimized infrared heating in combination with natural thermal radiation and convection. The baking time could be reduced by the higher amount of applied infrared radiation (Purlis, 2014).

Due to an increase of the radiation intensity in the infrared wavelength range between 3 and 6 μm the gelantinization and pasting of starch and therefore the formation of a fine elastic crumb needs less time, the oven loss will be smaller and more water is preserved in the baking good. The moisture content is higher and therefore the freshness of the baking good is extended. The second part of the baking process (browning, stabilization of the crust) is the same as in a conventional oven. Caused by the faster heating and crumb formation, the baking process is completed in less time. This entails a completely different baking process compared to conventional ovens. Therefore, the optimization of the corresponding production parameters must be optimized. For the optimization of processes, different approaches can be applied.

Using the response surface method, in a first step a design of all experiments is performed, then all experiments are carried out. Afterwards a none linear function is fitted to the results, whose extreme value is the optimum. A detailed description of the response surface method is given by Bezerra et al. (Bezerra et al., 2008). Response surface methodology has already been

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used for several applications in food processing (such as Flander et al. (2007); Turabi et al. (2007); Therdthai et al. (2002); Collar et al. (1999); Lahlali et al. (2008); Getachew and Chun (2016); Liu et al. (2016)).

As an alternative for optimization a sequential approach is the Nelder-Mead simplex method (Nelder and Mead, 1965), which were originally applied for the minimization of a function. Here, just a few experiments are performed initially and then depending on the results the parameters of the new experiment (new process parameters) are calculated. Depending on that outcome the next new experiment is calculated and so forth. The simplex method uses a hill climbing procedure to improve a process. A detailed description of the simplex method is given by Walters et al. (Walters et al., 1991).

The Nelder-Mead simplex method is here applied as alternative to the surface response method for optimization. The aim of this study is the optimization of the processing parameters of bread rolls in an oven with a special ceramic coating that increases the amount of infrared radiation during the baking process. The proofing time as well as the baking temperature are the influencing variables to improve the quality of the baked goods.

2. Optimization with the Nelder-Mead simplex method

The simplex method according to Nelder-Mead is a straight forward (Spendley et al., 1962) and fast method to optimize parameters within a few steps by minimizing or maximizing a quality or objective function. The simplex method is an alternative to the response surface method, however the optimization is carried out in an iterative approach. The Nelder-Mead simplex method can be performed within arbitrary dimensions, but the present study deals with just two: the proofing time and the baking temperature. Depending of these parameters the quality of the bread rolls are optimized. The optimal bread roll is defined by the results obtained with the conventional oven, which is specified by six parameters: The specific volume, baking loss, colour saturation of the surface, crispiness, crumb firmness and elasticity. The overall quality function is the sum of weighted squares (Equation 1 and 2) of the difference of actual parameter value and its target (optimal) value.

$$OQF = \sum_{i=1}^{6} QF_i \tag{1}$$

$$QF_i = \frac{(c_i - t_i)^2}{t_i \cdot \sigma_i} \tag{2}$$

OQF is the overall quality function, QF_i the quality function for each individual characteristic of the bread rolls, c_i the ith characteristic value of the bread roll, t_i is the ith target value of the characteristic variable, σ_i is its standard deviation. As one can see, if the quality function has a minimum (small value), then the same quality is obtained as in the conventional oven. If the confidence interval of OQF include zero, the optimal baking parameters for the ceramic coated oven were obtained and the optimization is termined. The error of the overall quality function was calculated according to the Gauss error propagation presented in Equation 3.

$$\Delta OQF = \sqrt{\sum_{i=1}^{6} (\frac{2 \cdot (c_i - t_i)}{t_i \cdot \sigma_i} \cdot \Delta c_i)^2} \tag{3}$$

Here ΔOQF is the error of the quality function, and Δc_i is the standard deviation of c_i. The confidence interval was calculated as $OQF \pm 3 \cdot \Delta OQF$. Applying the simplex algorithm with n parameters, one has to performe $n + 1$ initial experiments. Therefore, three initial experiments with different values of the parameters out of the search space will be carried out here. In the search space due to the three parameter values a triangle is obtained, describing the geometry of a simplex in two dimensions. Here, the three experiments can be represented by the following three vectors:

$$\vec{e_i} = \begin{pmatrix} t_i \\ T_i \end{pmatrix} \text{with } i = 1...3 \tag{4}$$

Where t_i represents the proofing time and T_i the baking temperature of the ith experiment. After the evaluation of the experiments using the OQF they are assessed to be the best ($\vec{b} = \vec{e}_x$), good ($\vec{g} = \vec{e}_y$) and worst ($\vec{w} = \vec{e}_z$) one. Therefore, each of the $\vec{e}_i$ has a corresponding OQF_i value with $OQF_x < OQF_y < OQF_z$. The next experiment is calculated out of the former experiment with Equation 5:

$$\vec{n} = \vec{b} + \vec{g} - \vec{w} \tag{5}$$

Using the calculated values of t and T of the vector $\vec{n}$ the new experiment is carried out. Then the assessment is carried out in the same way as before and so forth; this is called the fixed-size simplex or basic simplex algorithm. The disadvantages of this algorithm is, that its evolution depend of the first chosen triangles, if it is to small then many steps have to be carried out; if it is to large, one will jump over the optimal value. Therefore, Nelder and Mead proposed a modified simplex algorithm using Equation 6 for the fifth and the following experiments:

$$\vec{n} = \vec{M} + \gamma \cdot (\vec{M} - \vec{w}) \tag{6}$$

$$\vec{M} = \frac{1}{2} \cdot (\vec{g} + \vec{b}) \tag{7}$$

The new experimental point is $\vec{n}$, $\vec{M}$ is the mass centre of the best $\vec{b}$ and the good $\vec{g}$ assessed experiment, γ is the expanding/contracting-factor. This factor can get values between -0.5 and 1.5 depending on the values of the overall quality function of the new (OQF_n), the best (OQF_b), the good (OQF_g), and the worst (OQF_w) outcome (see Table 1). Depending on these cases the next experiment is calculated. For instance, if the outcome (OQF_n) of the new experiment $\vec{e}_n$ is better than the best outcome before $\vec{e}_b$ (which means $OQF_n < OQF_b$) the expanded simplex has to be applied. Therefore, the next experiment will be calculated using $\gamma = 1.5$ in Equation 6.

If the performed experiment $\vec{e}_e$ (e for expanded simplex) is then the new best, the new simplex will be obtained by the new, the before best and the before good one. The next simplex calculation will be performed with $\vec{e}_b$ (former $\vec{e}_e$), $\vec{e}_g$ (former $\vec{e}_b$) and $\vec{e}_w$ (former $\vec{e}_g$). The triangles might be getting smaller with every second iteration and approach to the optimum (Mathews and Fink, 1999). A condition for the termination must be checked after each new result. Here it was checked, if the confidence interval of OQF include zero. Using the simplex algorithm a problem can occur if there are local optima. Here it is expected to have only a global optimum, which should not far to seek. The scheme of all possible new experiments is presented in Figure 1. A detailed description of the method is given by Bezerra et al. (Bezerra et al., 2016) and Cerd et al. (Cerdà et al., 2016).

3. Materials and methods

3.1. Materials

The experiments were carried out with commercial wheat flour (type 550: defined as 0.51 - 0.63 % mineral content in dry matter, Rettenmeier GmbH und Co. KG, Horb a.N., Germany), water, commercial dry yeast (Saf-instant, LeSaffre, Bühl, Germany), baking malt (MeisterMarken Ulmer Spatz, Bingen am Rhein, Germany), hydrogenated peanut fat (BäKO, Ladenburg, Germany) and salt (Südsalz GmbH, Heilbronn, Germany).

3.2. Preparation of the bread rolls

The dough was prepared out of 1 kg wheat flour (corrected to 14 % moisture content), water (according to the farinograph water absorption), 1 g dry yeast, 1 g peanut fat, 3.5 g baking malt and 2 g salt per 100 g wheat flour. All ingredients were mixed for 1 minute (25 Hz) and kneaded for 5 minutes (50 Hz) in a spiral mixer (Diosna laboratory kneaders). The dough was processed in the common way for bread rolls. Proofing took place in a proofing chamber (WachtelStamm Petit Computer, Wachtel GmbH & Co., Hilden,Germany) at 30 °C and relative moisture of 80 % for 40 min for the standard. The bread rolls for the standard were baked at 220 °C upper and lower heat with 12 s of steam injection (initial upper heat: 235 °C, lower heat: 240 °C). The outlet was opened after 90 % of baking time to drag out the moisture. The baking experiments were performed in one oven which was equipped with both oven types (Piccolo I, Wachtel GmbH & Co., Hilden, Germany). The baking time was 20 min for the conventional oven and 16 min for the ceramic coated oven. The initial heat was adjusted in the ceramic coated oven according to the settings for the conventional ovens. The proofing time and the baking temperature were varied according to the calculated values of the simplex algorithm. The initial baking temperature was adjusted to the settings in the conventional oven (upper heat: 15 °C higher, lower heat: 20 °C higher).

3.3. Evaluation of the bread rolls

After cooling the bread rolls for 1 h, the mass (gravimetrically, all bread rolls) and the volume (VolScan Profiler, Stable Micro Systems, Surrey, England) were determined. The volume was measured using 10 bread rolls and extrapolated to all 30. The specific volume and the baking loss were calculated based on these values. The crust colour was determined by taking a picture of 5 bread rolls and evaluating a representing area of the crust according to the RGB colour space. The colour saturation was then calculated as value out of the HSV colour space (Equation 8).

$$Saturation = \begin{cases} 0 & R = G = B = 0, \\ \frac{(max-min)}{max} & \text{else } R, G, B \in [0, 255]. \end{cases} \tag{8}$$

A texture analyser (TA-XT2, Stable Micro Systems, England) was used with a modified AACC method (74-09) for texture profile analysis (TPA). Slices (25 mm thickness) were taken from the centre of 5 bread rolls. A 10 mm diameter probe (because of the small area of the bread roll crumb) and 5 kg load cell were used as measurement geometry. The three bread roll slices were two times compressed up to 40 % deformation with 15 s rest, the test speed was 1.7 mm/s; the crumb firmness and the elasticity were evaluated. The crispiness of 5 bread rolls were representative evaluated with the texture analyser. A plate with 104 mm diameter was used to compress the complete bread roll to a deformation of 40 %. The testing speed here was 1.67 mm/s. The maximum force was used as value for the crispiness. To provide a repeatable evaluation the bread rolls on the baking plate were divided in different groups. The grouping depicted in Figure 2 was defined for the evaluation methods. The aim was to have a balanced evaluation distribution across the baking plate.

3.4. Optimization with the Simplex algorithm

The starting experiments were defined according to pre-experiments performed in the ceramic coated oven. Here one result was that the baking of bread rolls will lead to good results when the bread rolls are proofed like the standard bread rolls and baked with 228 °C for 16 minutes. During further pre-experiments (data not shown) it was found out that proofing like the standard processing of bread rolls and baking at 218 °C und 15 min 49 s will lead to best baking results. The baking time of 16 minutes then was chosen. The starting experiments are presented in Table 2. The baking times for the first experiments were chosen according to normal baking conditions. The evaluation according to the quality parameters of bread rolls was rated with values out of the literature for the baking loss of 18-22 % (Stear, 1995; Wiggins and Cauvain, 2007). The specific volume of the bread rolls was chosen as 8 mL/g (determined in earlier studies, data not shown). The percentage standard deviation for the literature values was set to 5 %. The other target values were set when the standard baking experiments were performed in the conventional oven.

4. Results and Discussion

The parameter values of all performed experiments as well as the progress of the simplex optimization can be seen in Figure 3. The triangles were named after the resulting experiment, so triangle 4 corresponds to the calculated experiment 4 ($\vec{e}_{4n}$). In Table 3 the target values of all characteristics as well as the individual results for each experiment are presented. The start simplex (triangle: start simplex in Figure 3) were evaluated and the quality function of $\vec{e}_2$ was the worst. The next experiment was calculated as $\vec{e}_{4n}$ with mirroring $\vec{e}_2$ on the mass center of experiments $\vec{e}_1$ and $\vec{e}_3$ (triangle 4 is obtained). The evaluation of these performed experiments resulted in case number 1, which was $OQF_n > OQF_b > OQF_g$ (compare Table 1) and an expansion was performed $\vec{e}_{5e}$. After the evaluation the worst experiment of the new simplex was experiment $\vec{e}_1$ and again case number 2 was obtained, which lead to experiment $\vec{e}_{6n}$ (triangle 6). One contraction (γ = 0.5) was performed in triangle no. 7, because the new calculated and performed experiment $\vec{e}_{6n}$ was with its quality function value between the former good ($\vec{e}_3$) and worst ($\vec{e}_1$). The next experiment $\vec{e}_{8n}$ depicted in triangle no. 8 was calculated with a normal simplex (γ = 1) again. For the 9^{th} and 11^{th} triangle a negative contraction (γ = -0.5) was necessary, because the new calculated and performed experiments were worse than the worst before. After the calculation of the quality function for $\vec{e}_{11nc}$ and its error the simplex optimization was terminated. The errors of the quality function for $\vec{e}_{7c}$, $\vec{e}_{9nc}$ and $\vec{e}_{11nc}$ overlapped. In addition the value for the confidence interval of the objective function include zero for experiment $\vec{e}_{11nc}$.

To summarize the Nelder-Mead modified simplex method led within 11 experiments to an optimal baking result. The optimization was determined when the confidence interval of the values of the quality function include the value of zero. The obtained values for the quality function of the optimal baking parameters were smaller than the ones for the standard. This can be explained by the chosen values for the baking loss and the specific volume. They are not according to the standard, but out of literature or previous studies.

The quality function weighted every parameter nearly the same. The quality function did not always reflect the subjective impression of the baking results. This happened with the colour as presented in Figure 4. Here experiment $\vec{e}_{9nc}$ would be the best experiment regarding the optical evaluation.

5. Conclusion

In this contribution, the Nelder-Mead modified simplex algorithm has been applied for the optimization of two production parameters of bread rolls. The reason was to transfer a recipe of an ordinary oven to an oven with a ceramic coating. The fermentation time as well as the baking temperature were varied to obtain predefined characteristics of the bread rolls, which were defined as optimal and are obtained with a conventional oven. The definition of the quality function has to be considered thoughtful. Here a kind of least squares with respect to optimal values have been applied. Due to the fact that different characteristics were included in the quality function a weighting was performed, so that the values of each characteristic gave comparable contribution to the overall quality function. Using this approach within 11 experiments an optimal result were obtained. This example demonstrate, that the modified simplex is worth for optimization application in food processing, and can be used as alternative to the response surface optimization. Because the simplex algorithm is a kind of hill climbing procedure, no local optimum should be in the search space, which should be fulfilled not only in the present application. In the future more examples of simplex optimization for food processing will show up due to the straight forward calculation of the algorithm.

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Table 2: Starting experiments for the optimization of the processing parameters of bread rolls in the ceramic coated oven.

experiment	proofing time [min]	baking temperature [° C]
$\vec{e}_1$	70	260
$\vec{e}_2$	40	200
$\vec{e}_3$	90	180

Tables

Table 1: Cases for the evaluation of the new performed experiment.

case		Name (index)	γ
1	$OQF_n < OQF_b$	expanded simplex (e)	1.5
2	$OQF_b < OQF_n < OQF_g$	normal simplex (n)	1
3	$OQF_g < OQF_n < OQF_w$	contracted simplex (c)	-0.5
4	$OQF_w < OQF_n$	negative contracted simplex (nc)	-1.5

Table 3: Experiments for the Nelder-Mead simplex method and their results (mean and standard deviations) with the final quality function and its error. Experiment $\vec{e}_{5e}$ was performed in single.

	proofing time [min]	**baking temperature [°C]**	**spec. volume [mL/g]**	**baking loss [%]**	**colour saturation [-]**	**crispiness [-]**	**crumb firmness [N]**	**crumb elasticity [-]**	**quality function and its error**
STD	40	235	4.2 ± 0.1	18.5 ± 0.2	0.61 ± 0.08	26.1 ± 4.2	0.7 ± 0.1	1.04 ± 0.07	4.67 ± 0.33
target values			8.0 ± 0.4	17.0 ± 0.9	0.61 ± 0.08	26.1 ± 4.2	0.7 ± 0.1	1.04 ± 0.07	0
$\vec{e}_1$	70	260	5.7 ± 0.3	24.6 ± 0.1	0.77 ± 0.04	39.3 ± 3.7	1.0 ± 0.2	0.98 ± 0.02	8.87 ± 2.01
$\vec{e}_2$	40	200	3.7 ± 0.3	15.5 ± 0.5	0.64 ± 0.02	23.2 ± 4.1	1.4 ± 0.2	0.97 ± 0.01	11.96 ± 3.13
$\vec{e}_3$	90	180	4.8 ± 0.1	15.1 ± 0.1	0.54 ± 0.01	13.3 ± 3.5	0.7 ± 0.1	1.01 ± 0.05	5.04 ± 0.87
$\vec{e}_{4n}$	120	240	5.5 ± 0.1	21.3 ± 0.1	0.81 ± 0.01	24.1 ± 3.9	0.7 ± 0.1	1.10 ± 0.31	4.21 ± 0.59
$\vec{e}_{5e}$	140	250	6.8	26.0	0.82 ± 0.01	29.9± 3.7	0.6 ± 0.1	1.21 ± 0.44	7.31 ± 2.10
$\vec{e}_{6n}$	140	160	5.6 ± 0.1	15 ± 0.1	0.52 ± 0.02	8.7 ± 0.8	0.4 ± 0.01	1.02 ± 0.17	6.01 ± 0.32
$\vec{e}_{7c}$	122.5	185	5.8 ± 0.1	16.1 ± 0.1	0.64 ± 0.04	14.5 ± 2.2	0.7 ± 0.1	0.97 ± 0.02	2.90 ± 0.51
$\vec{e}_{8n}$	152.5	245	7.5 ± 0.6	24.2 ± 0.6	0.85 ± 0.02	28.0 ± 3.9	0.6 ± 0.1	1.11 ± 0.32	5.03 ± 0.90
$\vec{e}_{9nc}$	105.63	196.25	5.9 ± 0.3	16.9 ± 0.3	0.73 ± 0.08	16.7 ± 2.3	0.7 ± 0.1	1.03 ± 0.15	2.48 ± 0.74
$\vec{e}_{10n}$	108.13	141.25	4.1 ± 0.2	11.9 ± 0.2	0.52 ± 0.01	12.8 ± 4.1	0.7 ± 0.1	0.85 ± 0.05	8.77 ± 1.18
$\vec{e}_{11nc}$	117.03	215.31	6.7 ± 0.5	19.9 ± 0.5	0.78 ± 0.03	23.5 ± 1.9	0.8 ± 0.1	1.01 ± 0.13	1.77 ± 0.59

Figures

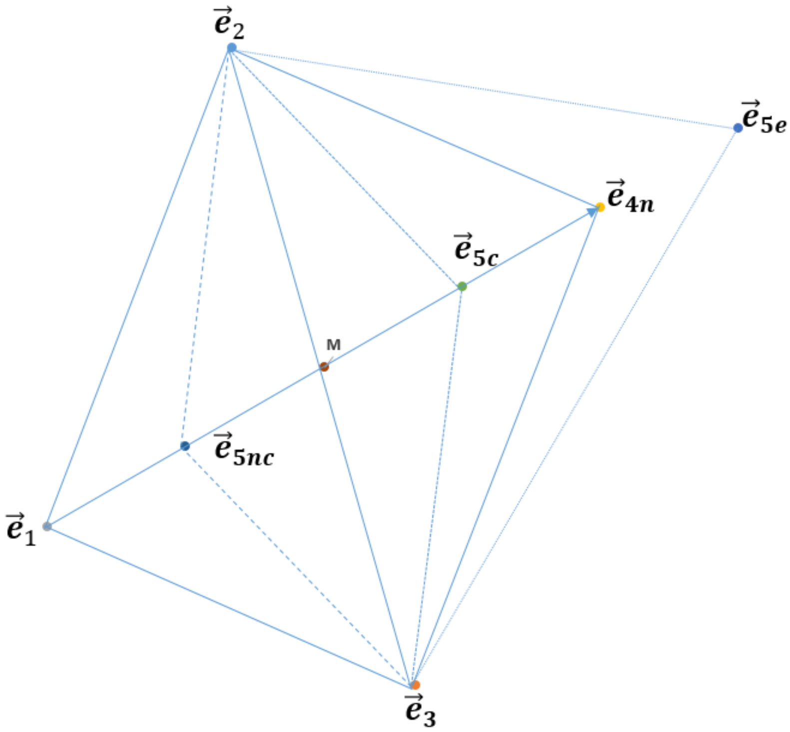

Figure 1: Schematic of the Nelder-Mead modified simplex method. $\vec{e}_1$, $\vec{e}_2$ and $\vec{e}_3$ are the starting experiments. $\vec{e}_4n$ is the new calculated experiment. Assessing this experiment, with respect to the cases of Table 1 the new parameter values are calculated, which are either $\vec{e}_{5nc}$ or $\vec{e}_{5c}$ or $\vec{e}_{5e}$ depending on the actual case.

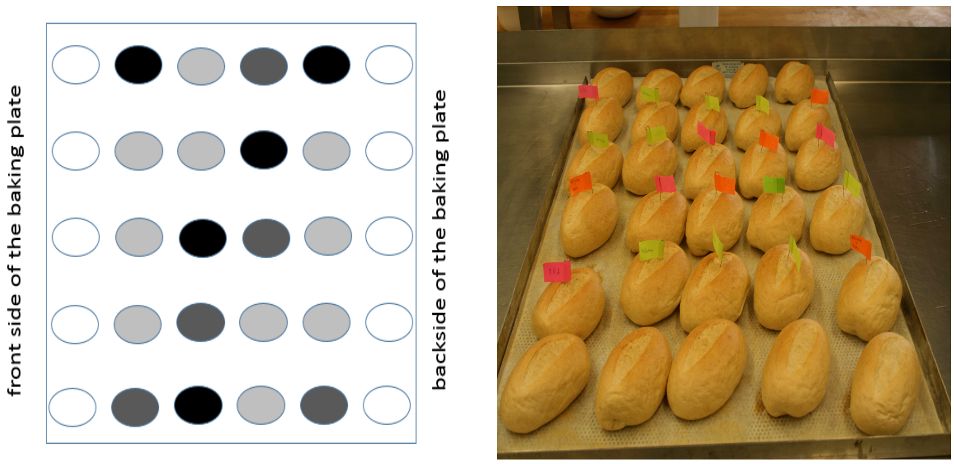

Figure 2: Grouping for the evaluation of the bread rolls (left); black: crispiness and colour saturation; dark grey: texture profile analysis; light grey: volume; white: not evaluated. Baking plate with tagged bread rolls for evaluation.

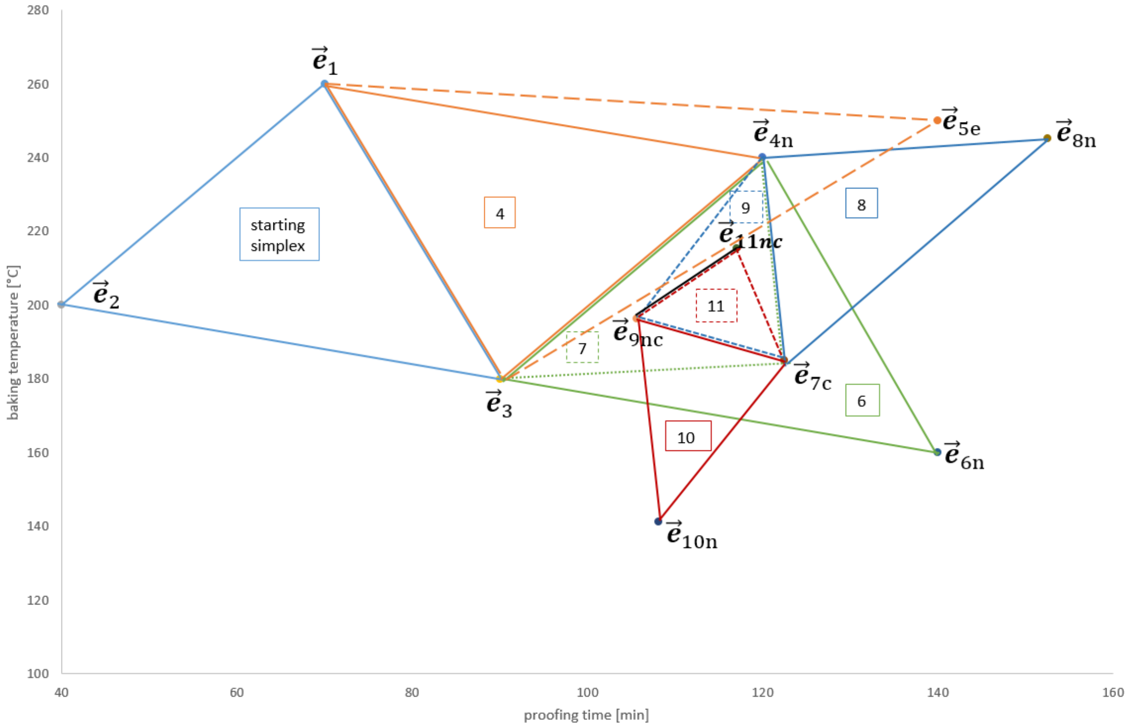

Figure 3: Progress of the Nelder-Mead simplex method for the optimization of the processing parameters for bread rolls.

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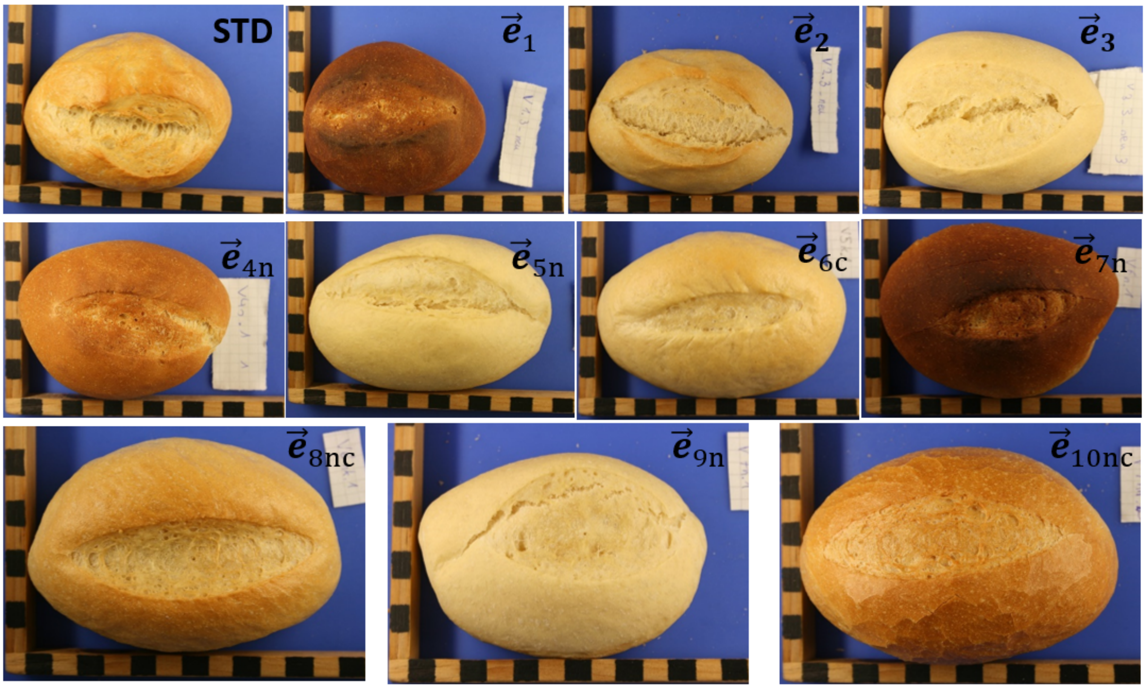

Figure 4: Crust colour pictures of the bread rolls. The standard (STD) and the starting experiments (line 1), the experiments $\vec{e}_{4n}$, $\vec{e}_{5n}$, $\vec{e}_{6c}$ and $\vec{e}_{7n}$ (line 2) and the last experiments $\vec{e}_{8nc}$, $\vec{e}_{9n}$ and the best experiment $\vec{e}_{10nc}$ (line 3).

Chapter 4

Discussion

Within this thesis the influence of gel from ground chia on the rheological behaviour of dough and the final product was investigated. The approach of using ground chia as gel seems to be fruitful to avoid competition between starch and chia with respect to the water uptake when the crumb formation during the baking process takes place. The evaluation of the pasting profiles of wheat flour suspensions with chia gel addition proved this assumption. The gel from ground chia affected the pasting properties. Different levels of added hydrocolloids do not influence the pasting properties significantly (Bárcenas *et al.*, 2009). Addition of ground chia leads to higher viscosities determined with amylograph measurements as determined by Švec *et al.* (2016). The evaluated doughs were affected in negative ways by the addition of high amounts of ground chia and subsequently water. The dough stability was then reduced and the resulting baked product was less porous and therefore compact. All doughs showed weakening regarding the rheometer measurements with incorporated gel from ground chia. The frequency sweep measurements show for all doughs a decrease with increasing content of gel from ground chia. The creep-recovery tests of the sweet pan bread doughs revealed that the zero viscosity η_0 decreased and the creep compliance increased with increasing chia gel contents. The weakening of the doughs may not absolutely be caused by the incorporated chia, but also by the additional water. There seems to be a kind of interaction between water, ground chia particles and wheat flour constituents. Nearly the same results were achieved for 2 % and 1 % of ground chia with 5 g/g and 10 g/g water, respectively. The increase in dough softness and stickiness is also reported for incorporating other sources of dietary fibre in baked products (Foschia *et al.*, 2013). The best results for incorporating gel from ground chia to wheat breads were obtained with 2 % and 1 % of ground chia with 5 g/g and 10 g/g water, respectively. The best results for sweet pan breads were obtained with 25 % fat replacement through gel from ground chia. This gel was prepared of 2.3 g ground chia with 5 g/g water. With these incorporations of gel from ground chia to the recipes the doughs could be processed easily and satisfying baking results were achieved. The specific volume was increased with incorporated chia gel and the retrogradation of the baked goods was decreased after storage. The dietary fibre content was increased and the fatty acid profile was presumably shifted to more ω-3 fatty acids in the wheat breads too.

For the sweet pan breads an increase was determined.
Summarizing the incorporation of a defined amount of gel from ground chia is possible without big disadvantages for the further processing of the doughs and the resulting baked products. The specific volumes were increased and the retrogradation over storage was decreased. The nutritional values of the evaluated baked products, wheat bread and sweet pan bread, were increased as well. Gel from ground chia can therefore be incorporated into bakery products for improving the nutritional values regarding the dietary fibre and ω-3 fatty acid contents. However it acts like a hydrocolloid.
In future it could be investigated how gel from ground chia is affected by the pre-hydration temperature. Some experiments on acidification of chia during the pre-hydration period could be interesting too. The amounts of chia and water were chosen based on literature values. The amount of water and chia could also be optimized. The application of chia for vegan or glutenfree products has been shown in the introduction, but there might be some open questions to be elucidated. The nutritional evaluation was done only exemplary, so this would be worth to analyse in future research projects too. The effects of our evaluated wheat breads and sweet pan breads on human health with respect to the absorption of the nutrients of chia should be evaluated in future research projects. There are not enough data yet to prove the nutritionally benefits properly.
In addition the optimization of the production parameters of bread rolls was performed using the Nelder-Mead simplex method. The main advantage of this optimization method is the stepwise proceeding. When the stop criterion is reached, here the optimal baking result, the optimization is terminated. Using an experimental design for this process the boundaries of the searching space need to be defined. All experiments have to be performed before the overall evaluation takes place. The optimization using design of experiments needs more time and more statistical evaluation. For the Nelder-Mead simplex method it is necessary to choose the quality function thoughtful. This is essential for the response surface method as well. It needs to mirror the desired characteristics and some weighting should be considered. The proofing time and the baking temperature were optimized for a new oven type with a ceramic coating. Within 11 experiments the optimum with a proofing time of 117 minutes

and a baking temperature of 215 °C for 16 minutes was determined. This example demonstrates, that the Nelder-Mead simplex method is worth for optimization application in food processing, and can be used as alternative to the response surface optimization. Due to the fact that the Nelder-Mead simplex method is a uphill or downhill search algorithm, the Nelder-Mead simplex optimization is especially beneficial if there is only one extreme value within the search space. It has been applied successfully here and it might appear in different other applications in future. Coming back to the first part of the work the optimal dosage of chia and water for vegan pound cakes might be a future application for the Nelder-Mead simplex method for example. All kinds of process or recipe optimization are conceivable in food applications. However, a new quality function depending on the characteristics of the desired product must be defined. The sensory evaluation and quality in contrast to the nutritional benefits might be a challenging task.

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Chapter 5

List of publications

With the knowledge and approval of the supervisor Professor Dr. Bernd Hitzmann following publications have been released and presentations have been performed. The scientific work presented in this thesis was partially conducted in cooperation with co-authors from the university of Hohenheim.

Co-authors

Influence of gel from ground chia (*Salvia hispanica* L.) for wheat bread production

By Viktoria Zettel, Anna Krämer, Florian Hecker and Bernd Hitzmann published in European Food Research and Technology.

Anna Krämer assisted in the experimental part to characterize the doughs and Florian Hecker provided the knowledge of processing the doughs and helped to draw correct conclusions in the beginning.

Peer reviewed publications

- Zettel, V., Krämer, A., Hecker, F., Hitzmann, B. (2015). Influence of gel from ground chia (*Salvia hispanica* L.) for wheat bread production. *European Food Research and Technology* 240 (3), 655-662.
- Zettel, V. and Hitzmann, B. (2016). Chia (*Salvia hispanica* L.) as fat replacer in sweet pan breads. *International Journal of Food Science & Technology* 51 (6), 1425–1432.
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Other publications

- Zettel, V., Krämer, A., Hecker, F., Hitzmann, B. (2014). Einsatz von Chiagelen in Weizenbroten. *brot+backwaren* (6), 42-46. URL http://www.brotundbackwaren.de/files/f2m-media/pdf/archiv/epaper/bub/2014/683kh73x/bub 2014-06 42 Einsatz von Chiagelen in Weizenbroten.pdf.

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- Zettel, V., Hecker, F., Hitzmann, B., 2015b. Wie wirkt sich STIR auf das Backergebnis aus? *brot+backwaren* (2), 44-49. URL http://www.brotundbackwaren.de/heftinhalte/brotbackwaren-ausgabe-2 2015.html?file=files/f2m-media/pdf/archiv/epaper/bub/2015/29mx6j34/bub 2015-02 44 Wie wirkt sich STIR auf das Backergebnis aus.pdf.

- Zettel, V., Hitzmann, B. (2016). Chia (*Salvia hispanica* L.) as alternative fat source in pound cakes. cereal technology. *Accepted.*

Poster

- Zettel, V., Krämer, A., Hecker, F., Hitzmann, B. (2014). Gel from ground chia (*Salvia hispanica* L.) as hydrocolloid for wheat bread production. Poster presented at the AACC Anual meeting 2014, October 5-8, Providence, Rhode Island, U.S.A. URL http://www.aaccnet.org/meetings/Documents/2014Abstracts/2014P62.htm.

- Zettel, V., Gehringer, J., Hitzmann, B. (2015). Gluten free porridge with accustomed rheological properties. Poster presented at the 7th International Symposium on Food Rheology and Structure, June 7-11, Zurich, Switzerland. URL http://www.isfrs.ethz.ch/proc/2015 abst/Abstracts 2015.

- Zettel, V., Krämer, A., Hecker, F., Hitzmann, B. (2015). Effects of gel from ground chia (*Salvia hispanica* L.) on the rheological properties of wheat dough and bread. Poster presented at the 7th International Symposium on Food Rheology and Structure, June 7-11, Zurich, Switzerland. URL http://www.isfrs.ethz.ch/proc/2015 abst/Abstracts 2015.

- Zettel, V., Paquet-Durand, O., Hecker, F., Hitzmann, B. (2015). Mit Hilfe der Prozessanalytik auf dem Weg zum intelligenten Gärschrank. Poster presented at the 11th Kolloquium Prozessanalytik, December 1-2, Vienna, Austria. The poster was awarded with the 1st poster price. URL http://www.arbeitskreis-prozessanalytik.de/images/ stories/Veranstal- tungen/Kolloquien/11 kolloquium 2015/Tagungsband 11 Kolloquium final.pdf.

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- Zettel, V., Paquet-Durand, O., Hecker, F., Hitzmann, B. (2016). Heading for an intelligent proofing chamber through process analytics. Poster presented at the 15th International Cereal and Bread Congress, April 18-21, Istanbul, Turkey.

- Karademir, E., Zettel, V., Hitzmann, B. (2016). Effects of Psyllium Husk (*Plantago ovata*) on Wheat Bread and its Dough. Poster presented at the 15th International Cereal and Bread Congress, April 18-21, Istanbul, Turkey.

Oral presentations

- Zettel, V., Krämer, A., Hecker, F., Hitzmann, B. (2015). Chiagele in Weizenbroten - für gesunde Ernährung und bessere Brotqualität. Vortrag bem 52. Wissenschaftlichen Kongress der DGE in Halle-Wittenberg, 11-13 März, Halle, Germany.

- Zettel, V., Paquet-Durand, O., Hecker, F., Hitzmann, B. (2015). Chia als mögliches Additiv in der Brotherstellung. Vortrag bei der 4. Frühjahrstagung des Weihenstephaner Instituts für Getreideforschung (WIG), 21.-22. April, Freising, Deutschland.

- Moll, S., Zettel, V., Hitzmann, B. (2016). Sonnenblumenprotein als mögliches Additiv bei der Herstellung von Weizenvollkornbrot. Vortrag bei der 5. Frühjahrstagung des Weihenstephaner Instituts für Getreideforschung (WIG), 05.-06. April, Freising, Deutschland.

- Zettel, V., Hitzmann, B. (2015). Superfood: Funktionelle Eigenschaften von Chia-Gelen in Weizenteigen- und Massen. Vortrag beim FORUM Fine Bakery am 10. November in Solingen, Germany.

- Zettel, V., Paquet-Durand, O., Hecker, F., Hitzmann, B. (2014). Entwicklung einer intelligenten Gärsteuerung zur optimierten Herstellung von Teiglingen mittels digitaler Bildauswertung und erfahrungs-basierter Fuzzyregelung. Vortrag in der Sitzung des Projektbegleitenden Ausschusses (AIF-Projekt 18123 N) am 14. November in Freising, Germany.

- Zettel, V., Paquet-Durand, O., Hecker, F., Hitzmann, B. (2015). Entwicklung einer intelligenten Gärsteuerung zur optimierten Herstellung von Teiglingen mittels digitaler Bildauswertung und erfahrungs-basierter Fuzzyregelung. Vortrag in der Sitzung des Projektbegleitenden Ausschusses (AIF-Projekt 18123 N) am 24. September in Freising, Germany.

- Zettel, V., Hitzmann, B., 2016b. Einsatz von Chiagelen als Fettersatz in Kastenstuten. Vortrag bei der 5. Frühjahrstagung des Weihenstephaner Instituts für Getreideforschung (WIG), 05.-06. April, Freising, Deutschland.

Annex

Table 2: Compilation of publications on chia as from 1th of June 2016. Y: year of publication, T: type of publication as follows: A: Article, B: Book, i. B.: in Book

author, editor or publisher	Y	title	T	journal	DOI, URL or ISBN
Betancur-Ancona, David; Segura-Campos, Maira Rubí	2016	Salvia hispanica L	B		1634843959
Bruno Eduardo Campos; Thiago Dias Ruivo; Mônica R. da Silva Scapim; Grasiele Scaramal Madrona; Rita de C. Bergamasco	2016	Optimization of the mucilage extraction process from chia seeds and application in ice cream as a stabilizer and emulsifier	A	LWT - Food Science and Technology	10.1016/j.lwt.2015.09.021
Citelli, Marta; Fonte-Faria, Thaís; Vargas-Silva, Simone; Barja-Fidalgo, Christina	2016	Dietary supplementation with chia (Salvia hispanica L.) oil reduces the complications caused by high fat diet-induced obesity	A	The FASEB Journal	
Da Silva, Bárbara Pereira; Dias, Desirrê Morais; de Castro Moreira, Maria Eliza; Toledo, Renata Celi Lopes; da Matta, Sérgio Luis Pinto; Della Lucia, Ceres Mattos; Martino, Hércia Stampini Duarte; Pinheiro-Sant'Ana, Helena Maria	2016	Chia Seed Shows Good Protein Quality, Hypoglycemic Effect and Improves the Lipid Profile and Liver and Intestinal Morphology of Wistar Rats	A	Plant Foods for Human Nutrition	10.1007/s11130-016-0543-8
Goh, Kelvin Kim Tha; Matia-Merino, Lara; Chiang, Jie Hong; Quek, Ruisong; Soh, Stephanie Jun Bing; Lentle, Roger G.	2016	The physico-chemical properties of chia seed polysaccharide and its microgel dispersion rheology	A	Carbohydrate Polymers	10.1016/j.carbpol.2016.04.126
Huerta, Katira da Mota; Alves, Jamila dos Santos; Silva, Ariádni Franco Coelho da; Kubota, Ernesto Hashime; Rosa, Claudia Severo da	2016	Sensory response and physical characteristics of gluten-free and gum-free bread with chia flour	A	Food Sci. Technol (Campinas) (Food Science and Technology (Campinas))	10.1590/1678-457X.0032
Jenkins, Alexandra L.; Brissette, Christy; Jovanovski, Elena; Au-Yeung, Fei; Ho, Hoang Vi Thanh; Zurbau, Andreea; Sievenpiper, John; Vuksan, Vladimir	2016	Effect of Salba-Chia (Salvia Hispanica L), an Ancient Seed, in the Treatment of Overweight and Obese Patients with Type 2 Diabetes: A Double-blind, Parallel, Randomized Controlled Trial	A	The FASEB Journal	http://www.fasebj.org/content/30/1_Supplement/126.2.short
Loaiza, María Armida Patricia Porras; López-Malo, Aurelio; Jiménez-Munguía, María Teresa	2016	Nutraceutical Properties of Amaranth and Chia Seeds	i. B.	Functional Properties of Traditional Foods (978-1-4899-7662-8)	10.1007/978-1-4899-7662-8_13
Possenti, Jean Carlo; Donazzolo, Joel; Gullo, Karina; Voss, Larissa Corradi; Danner, Moeses Andrigo	2016	Influence of temperature and substrate on chia seeds germination	A	Científica	10.15361/1984-5529.2016v44n2p235-238
Segura-Campos, Maira Rubí; Chel-Guerrero, Luis Antonio; Betancur-Ancona, David Abram	2016	Salvia hispanica: Nutritional and Functional Potential	i. B.	Functional Properties of Traditional Foods (978-1-4899-7662-8)	10.1007/978-1-4899-7662-8_8
Segura-Campos, Maira Rubí; Chel-Guerrero, Luis Antonio; Castellanos-Ruelas, Arturo Francisco; Betancur-Ancona, David Abram	2016	Chemical Characterization of Mexican Chia (Salvia hispanica L.) Flour	i. B.	Functional Properties of Traditional Foods (978-1-4899-7662-8)	10.1007/978-1-4899-7662-8_10
Segura-Campos, Maira Rubí; Chel-Guerrero, Luis Antonio; Rosado-Rubio, José Gabriel; Betancur-Ancona, David Abram	2016	Biofunctionality of Chia (Salvia hispanica L.) Protein Hydrolysates	i. B.	Functional Properties of Traditional Foods (978-1-4899-7662-8)	10.1007/978-1-4899-7662-8_14
Silva, Herman; Garrido, Marco; Baginsky, Cecilia; Valenzuela, Alfonso; Morales, Luis; Valenzuela, Cristián; Pavez, Sebastián; Alister, Sebastián	2016	Effect of water availability on growth, water use efficiency and omega 3 (ALA) content in two phenotypes of chia (Salvia hispanica L.) established in the arid Mediterranean zone of Chile	A	Agricultural Water Management	10.1016/j.agwat.2016.04.028
Timilsena, Yakindra Prasad; Adhikari, Raju; Kasapis, Stefan; Adhikari, Benu	2016	Molecular and functional characteristics of purified gum from Australian chia seeds	A	Carbohydrate Polymers	10.1016/j.carbpol.2015.09.035
Ayerza, R.	2016	Crop year effects on seed yields, growing cycle length, and chemical composition of chia (Salvia hispanica L) growing in Ecuador and Bolivia	A	Emir. J. Food Agric (Emirates Journal of Food and Agriculture)	10.9755/ejfa.2015-05-323
Zettel, Viktoria; Hitzmann, Bernd	2016	Chia (Salvia hispanica L.) as fat replacer in sweet pan breads	A	Int J Food Sci Technol (International Journal of Food Science & Technology)	10.1111/ijfs.13110

Rodríguez-Abello, Diana; Ramírez-Avilés, Luis; Navarro-Alberto, Jorge; Zamora-Bustillos, Roberto	2016	Performance of growing rabbits fed increasing levels of discarded Salvia hispanica L. (chia) seed	A	Tropical Animal Health and Production	10.1007/s11250-016-1043-4
Guiotto, Estefania N.	2016	Stability of Oil-in-Water Emulsions with Sunflower (Helianthus annuus L.) and Chia (Salvia hispanica L.) By-Products	A	Journal of the American Oil Chemists' Society	10.1007/s11746-015-2746-9
da Silva, C. S., Kanaguchi, G., Monteiro, C. R. A., Feder, D., Azzalis, L. A., Perazzo, F. F., Maifrino, L. B. M., Ornelas, E., Rosa, P. C. P., & Fonseca, F. L. A.	2016	Biochemical parameters and Histomorphometric cardicac evaluation among Wistar rats treated with chia seed (Salvia hispanica L.): Experimental model	A	African Journal of Pharmacy and Pharmacology	10.5897/AJPP2015.4478
Silva, L. G.; Bunkers, J.; Paula, E. M.; Shenkoru, T.; Yeh, Y.; Amorati, B.; Holcombe, D.; Faciola, A. P.	2016	Effects of flaxseed and chia seed on ruminal fermentation, nutrient digestibility, and long-chain fatty acid flow in a dual-flow continuous culture system1	A	Journal of Animal Science	10.2527/jas.2015-9750
Ullah, Rahman; Nadeem, Muhammad; Ayaz, Muhammad; Imran, Muhammad; Tayyab, Muhammad	2016	Fractionation of chia oil for enrichment of omega 3 and 6 fatty acids and oxidative stability of fractions	A	Food Science and Biotechnology	10.1007/s10068-016-0006-x
Dick, Melina; Henrique Pagno, Carlos; Haas Costa, Tania Maria; Gomaa, Ahmed; Subirade, Muriel; Oliveira Rios, Alessandro de; Hickmann Fl ôres, Simone	2016	Edible films based on chia flour: Development and characterization	A	Journal of Applied Polymer Science	10.1002/app.42455
Yakindra Prasad Timilsena; Raju Adhikari; Stefan Kasapis; Benu Adhikari	2016	Molecular and functional characteristics of purified gum from Australian chia seeds	A	Carbohydrate Polymers	10.1016/j.carbpol.2015.09.035
Yakindra Prasad Timilsena; Bo Wang; Raju Adhikari; Benu Adhikari	2016	Preparation and characterization of chia seed protein isolate-chia seed gum complex coacervates	A	Food Hydrocolloids	10.1016/j.foodhyd.2015.07.033
I. švec; M. Hrušková; I. Jurinová	2016	Pasting characteristics of wheat-chia blends	A	Journal of Food Engineering	10.1016/j.jfoodeng.2015.04.030
L.A. Escalona-García; R. Pedroza-Islas; R. Natividad; M.E. Rodríguez-Huezo; H. Carrillo-Navas; C. Pérez-Alonso	2016	Oxidation kinetics and thermodynamic analysis of chia oil microencapsulated in a whey protein concentrate-polysaccharide matrix	A	Journal of Food Engineering	10.1016/j.jfoodeng.2015.12.009
Bruno Eduardo Campos; Thiago Dias Ruivo; Mônica R. da Silva Scapim; Grasiele Scaramal Madrona; Rita de C. Bergamasco	2016	Optimization of the mucilage extraction process from chia seeds and application in ice cream as a stabilizer and emulsifier	A	LWT - Food Science and Technology	10.1016/j.lwt.2015.09.021
T. Pintado; A.M. Herrero; F. Jiménez-Colmenero; C. Ruiz-Capillas	2016	Strategies for incorporation of chia (Salvia hispanica L.) in frankfurters as a health-promoting ingredient	A	Meat Science	10.1016/j.meatsci.2015.12.009
Montanher, Paula Fernandes; e Silva, Beatriz Costa; Bonafé, Elton Guntendorfer; Carbonera, Fabiana; dos Santos, Hevelyse Munise Celestino; Lima Figueiredo, Ingrid de; Maruyama, Swami Arêa; Matsushita, Makoto; Visentainer, Jesuí Vergílio	2015	Effects of diet supplementation with chia (Salvia hispanica L.) oil and natural antioxidant extract on the omega-3 content and antioxidant capacity of Nile Tilapia fillets	A	European Journal of Lipid Science and Technology	10.1002/ejlt.201400334
Souza, Aloisio H. P.; Gohara, Aline K.; Rotta, Eliza M.; Chaves, Marcia A.; Silva, Claudia M.; Dias, Lucia F.; Gomes, Sandra T. M.; Souza, Nilson E.; Matsushita, Makoto	2015	Effect of the addition of chia's by-product on the composition of fatty acids in hamburgers through chemometric methods	A	Journal of the Science of Food and Agriculture	10.1002/jsfa.6764
Patel, Seema	2015	Newest and Robust Entrant to the Functional Food Sector: Chia Seeds	i. B.	Emerging Bioresources with Nutraceutical and Pharmaceutical Prospects	10.1007/978-3-319-12847-4_7
Kutbay, H. Güray	2015	Chapter 9: Mountainous Vegetation of Central Black Sea Region	i. B.	Climate Change Impacts on High-Altitude Ecosystems	10.1007/978-3-319-12859-7_9
Bochicchio, Rocco	2015	Innovative Crop Productions for Healthy Food: The Case of Chia (Salvia hispanica L.)	A	The Sustainability of Agro-Food and Natural Resource Systems in the Mediterranean Basin	10.1007/978-3-319-16357-4_3
Zettel, V.; Krämer, A.; Hecker, F.; Hitzmann, B.	2015	Influence of gel from ground chia (Salvia hispanica L.) for wheat bread production	A	European Food Research and Technology	10.1007/s00217-014-2368-8

Amato, Mariana	2015	Nutritional quality of seeds and leaf metabolites of Chia (Salvia hispanica L.) from Southern Italy	A	European Food Research and Technology	10.1007/s00217-015-2488-9
Vara-Messler, Marianela	2015	Increased dietary levels of a-linoleic acid inhibit mammary tumor growth and metastasis	A	European Journal of Nutrition	10.1007/s00394-015-1096-6
Bolaãos, Daniela	2015	Elemental Analysis of Amaranth, Chia, Sesame, Linen, and Quinoa Seeds by ICP-OES: Assessment of Classification by Chemometrics	A	Food Analytical Methods	10.1007/s12161-015-0217-4
Luna Pizarro, Patricia	2015	Functional bread with n-3 alpha linolenic acid from whole chia (Salvia hispanica L.) flour	A	Journal of Food Science and Technology	10.1007/s13197-014-1477-5
Azeem, Waqar	2015	Stabilization of winterized cottonseed oil with chia (Salvia hispanica l.) seed extract at ambient temperature	A	Journal of Food Science and Technology	10.1007/s13197-015-1823-2
Ullah, Rahman	2015	Nutritional and therapeutic perspectives of Chia (Salvia hispanica L.): a review	A	Journal of Food Science and Technology	10.1007/s13197-015-1967-0
Ouzounidou, Georgia	2015	Effects of soil pH and arbuscular mycorrhiza (AM) inoculation on growth and chemical composition of chia (Salvia hispanica L.) leaves	A	Brazilian Journal of Botany	10.1007/s40415-015-0166-6
Sandra Karina Velázquez-Gutiérrez; Ana Cristina Figueira; María Eva Rodríguez-Huezo; Angélica Román-Guerrero; Hector Carrillo-Navas; César Pérez-Alonso	2015	Sorption isotherms, thermodynamic properties and glass transition temperature of mucilage extracted from chia seeds (Salvia hispanica L.)	A	Carbohydrate Polymers	10.1016/j.carbpol.2014.11.068
Melina Dick; Tania Maria Haas Costa; Ahmed Gomaa; Muriel Subirade; Alessandro de Oliveira Rios; Simone Hickmann Fl ôres	2015	Edible film production from chia seed mucilage: Effect of glycerol concentration on its physicochemical and mechanical properties	A	Carbohydrate Polymers	10.1016/j.carbpol.2015.05.040
T. Pintado; C. Ruiz-Capillas; F. Jiménez-Colmenero; P. Carmona; A.M. Herrero	2015	Oil-in-water emulsion gels stabilized with chia (Salvia hispanica L.) and cold gelling agents: Technological and infrared spectroscopic characterization	A	Food Chemistry	10.1016/j.foodchem.2015.04.024
G. Avila-de la Rosa; J. Alvarez-Ramirez; E.J. Vernon-Carter; H. Carrillo-Navas; C. Pérez-Alonso	2015	Viscoelasticity of chia (Salvia hispanica L.) seed mucilage dispersion in the vicinity of an oil-water interface	A	Food Hydrocolloids	10.1016/j.foodhyd.2015.03.017
Rafaela da Silva Marineli; Sabrina Alves Lenquiste; érica Aguiar Moraes; Mário Roberto Maróstica Jr.	2015	Antioxidant potential of dietary chia seed and oil (Salvia hispanica L.) in diet-induced obese rats	A	Food Research International	10.1016/j.foodres.2015.07.039
Yakindra Prasad Timilsena; Raju Adhikari; Stefan Kasapis; Benu Adhikari	2015	Rheological and microstructural properties of the chia seed polysaccharide	A	International Journal of Biological Macromolecules	10.1016/j.ijbiomac.2015.09.040
Samuel Verdú; Francisco Vásquez; Eugenio Ivorra; Antonio J. Sánchez; Jose M. Barat; Raúl Grau	2015	Physicochemical effects of chia (Salvia hispanica) seed flour on each wheat bread-making process phase and product storage	A	Journal of Cereal Science	10.1016/j.jcs.2015.05.011
Liliana Sierra; Julieta Roco; Gabriela Alarcon; Mirta Medina; Carina Van Nieuwenhove; María Peral de Bruno; Susana Jerez	2015	Dietary intervention with Salvia hispanica (Chia) oil improves vascular function in rabbits under hypercholesterolaemic conditions	A	Journal of Functional Foods	10.1016/j.jff.2015.02.042
M.I. Capitani; L.J. Corzo-Rios; L.A. Chel-Guerrero; D.A. Betancur-Ancona; S.M. Nolasco; M.C. Tomás	2015	Rheological properties of aqueous dispersions of chia (Salvia hispanica L.) mucilage	A	Journal of Food Engineering	10.1016/j.jfoodeng.2014.09.043
Mario Cueto; Josefina Porras-Saavedra; Abel Farroni; Liliana Alamilla-Beltrán; Regine Schoenlechner; Gerhard Schleining; Pilar Buera	2015	Physical and mechanical properties of maize extrudates as affected by the addition of chia and quinoa seeds and antioxidants	A	Journal of Food Engineering	10.1016/j.jfoodeng.2015.07.027
Jeffrey A. Byars; Mukti Singh	2015	Properties of extruded chia-corn meal puffs	A	LWT - Food Science and Technology	10.1016/j.lwt.2014.06.036
Coelho, Michele Silveira; Salas-Mellado, Myriam de las Mercedes	2015	Effects of substituting chia (Salvia hispanica L.) flour or seeds for wheat flour on the quality of the bread	A	LWT - Food Science and Technology	10.1016/j.lwt.2014.10.033
Steffolani, Eugenia; Martinez, Mario M.; León, Alberto E.; Gómez, Manuel	2015	Effect of pre-hydration of chia (Salvia hispanica L.), seeds and flour on the quality of wheat flour breads	A	LWT - Food Science and Technology	10.1016/j.lwt.2014.12.056

Mária Herminia Ferrari Felisberto; Adriana Lucia Wahanik; Cristiane Rodrigues Gomes-Ruffi; Maria Teresa Pedrosa Silva Clerici; Yoon Kil Chang; Caroline Joy Steel	2015	Use of chia (Salvia hispanica L.) mucilage gel to reduce fat in pound cakes	A	LWT - Food Science and Technology	10.1016/j.lwt.2015.03.114
Domancar Orona-Tamayo; María Elena Valverde; Blanca Nieto-Rendón; Octavio Paredes-López	2015	Inhibitory activity of chia (Salvia hispanica L.) protein fractions against angiotensin I-converting enzyme and antioxidant capacity	A	LWT - Food Science and Technology	10.1016/j.lwt.2015.05.033
Rafaela da Silva Marineli; Carolina Soares Moura; érica Aguiar Moraes; Sabrina Alves Lenquiste; Pablo Christiano Barboza Lollo; Priscila Neder Morato; Jaime Amaya-Farfan; Mário Roberto Maróstica Jr.	2015	Chia (Salvia hispanica L.) enhances HSP, PGC-1a expressions and improves glucose tolerance in diet-induced obese rats	A	Nutrition	10.1016/j.nut.2014.11.009
M.L. Martínez; M.I. Curti; P. Roccia; J.M. Llabot; M.C. Penci; R.M. Bodoira; P.D. Ribotta	2015	Oxidative stability of walnut (Juglans regia L.) and chia (Salvia hispanica L.) oils microencapsulated by spray drying	A	Powder Technology	10.1016/j.powtec.2014.10.031
Vanesa Y. Ixtaina; Luciana M. Julio; Jorge R. Wagner; Susana M. Nolasco; Mabel C. Tomás	2015	Physicochemical characterization and stability of chia oil microencapsulated with sodium caseinate and lactose by spray-drying	A	Powder Technology	10.1016/j.powtec.2014.11.006
O. Urrutia; B. Soret; K. Insausti; J.A. Mendizabal; A. Purroy; A. Arana	2015	The effects of linseed or chia seed dietary supplementation on adipose tissue development, fatty acid composition, and lipogenic gene expression in lambs	A	Small Ruminant Research	10.1016/j.smallrumres.2014.12.008
Coorey, Ranil; Novinda, Agnes; Williams, Hannah; Jayasena, Vijay	2015	Omega-3 Fatty Acid Profile of Eggs from Laying Hens Fed Diets Supplemented with Chia, Fish Oil, and Flaxseed	A	Journal of Food Science	10.1111/1750-3841.12735
Rodrigues, J.B; Paixão, J. A.; Cruz, A. G.; Bolini, H.M.A.	2015	Chocolate Milk with Chia Oil: Ideal Sweetness, Sweeteners Equivalence, and Dynamic Sensory Evaluation Using a Time-Intensity Methodology	A	Journal of Food Science	10.1111/1750-3841.13120
de Mello, Bruna Tais F.; dos Santos Garcia, Vitor A.; da Silva, Camila	2015	Ultrasound-Assisted Extraction of Oil from Chia (Salvia hispanica L.) Seeds: Optimization Extraction and Fatty Acid Profile	A	Journal of Food Process Engineering	10.1111/jfpe.12298
Leiva, GE.; šegatin, N.; Mazzobre, MF.; Abramovič , H.; Abram, V.; Vidrih, R.; Buera, MP. and Poklar Ulrih, N.	2015	Multi-analytical Approach to Oxidative Stability of Unrefined Argan, Chia, Rosa Mosqueta and Olive Oils	A	Journal of Nutrition & Food Sciences	10.4172/2155-9600.1000450
Inglett, George E.; Chen, Diejun; Liu, Sean	2014	Physical properties of sugar cookies containing chia-oat composites	A	Journal of the Science of Food and Agriculture	10.1002/jsfa.6674
Almog, Limor	2014	Bridging cross-cultural gaps: monitoring herbal use during chemotherapy in patients referred to integrative medicine consultation in Israel	A	Supportive Care in Cancer	10.1007/s00520-014-2261-9
Toscano, Luciana Tavares	2014	Chia Flour Supplementation Reduces Blood Pressure in Hypertensive Subjects	A	Plant Foods for Human Nutrition	10.1007/s11130-014-0452-7
Silva, Beatriz Costa e	2014	Incorporation of Omega-3 Fatty Acids in Nile Tilapia (Oreochromis niloticus) Fed Chia (Salvia hispanica L.) Bran	A	Journal of the American Oil Chemists' Society	10.1007/s11746-013-2391-0
Guiotto, Estefania N.	2014	Effect of Storage Conditions and Antioxidants on the Oxidative Stability of Sunflower-Chia Oil Blends	A	Journal of the American Oil Chemists' Society	10.1007/s11746-014-2410-9
Oliviert Martínez-Cruz; Octavio Paredes-López	2014	Phytochemical profile and nutraceutical potential of chia seeds (Salvia hispanica L.) by ultra high performance liquid chromatography	A	Journal of Chromatography A	10.1016/j.chroma.2014.04.007
Ganesh Diwakar; Jatinder Rana; Lisa Saito; Doug Vredeveld; Dorothy Zemaitis; Jeffrey Scholten	2014	Inhibitory effect of a novel combination of Salvia hispanica (chia) seed and Punica granatum (pomegranate) fruit extracts on melanin production	A	Fitoterapia	10.1016/j.fitote.2014.05.021

Lara Costantini; Lea Lukš ič ; Romina Molinari; Ivan Kreft; Giovanni Bonafaccia; Laura Manzi; Nicolò Merendino	2014	Development of gluten-free bread using tartary buckwheat and chia flour rich in flavonoids and omega-3 fatty acids as ingredients	A	Food Chemistry	10.1016/j.foodchem.2014.05.095
Eric C. Martens; Amelia G. Kelly; Alexandra S. Tauzin; Harry Brumer	2014	The Devil Lies in the Details: How Variations in Polysaccharide Fine-Structure Impact the Physiology and Evolution of Gut Microbes	A	Journal of Molecular Biology	10.1016/j.jmb.2014.06.022
Inglett, George E.; Chen, Diejun; Liu, Sean X.; Lee, Suyong	2014	Pasting and rheological properties of oat products dry-blended with ground chia seeds	A	LWT - Food Science and Technology	10.1016/j.lwt.2013.07.011
Rafaela da Silva Marineli; érica Aguiar Moraes; Sabrina Alves Lenquiste; Adriana Teixeira Godoy; Marcos Nogueira Eberlin; Mário Roberto Maróstica Jr	2014	Chemical characterization and antioxidant potential of Chilean chia seeds and oil (Salvia hispanica L.)	A	LWT - Food Science and Technology	10.1016/j.lwt.2014.04.014 [t]
S. Cofrades; J.A. Santos-López; M. Freire; J. Benedí; F.J. Sánchez-Muniz; F. Jiménez-Colmenero	2014	Oxidative stability of meat systems made with W1/O/W2 emulsions prepared with hydroxytyrosol and chia oil as lipid phase	A	LWT - Food Science and Technology	10.1016/j.lwt.2014.06.051 [b]
Coorey, Ranil; Tjoe, Audrey; Jayasena, Vijay	2014	Gelling Properties of Chia Seed and Flour	A	Journal of Food Science	10.1111/1750-3841.12444
Porras-Loaiza, Patricia; Jiménez-Munguía, María T.; Sosa-Morales, María Elena; Palou, Enrique; López-Malo, Aurelio	2014	Physical properties, chemical characterization and fatty acid composition of Mexican chia (Salvia hispanica L.) seeds	A	International Journal of Food Science & Technology	10.1111/ijfs.12339
Steffolani, Eugenia; La Hera, Esther de; Pérez, Gabriela; Gómez, Manuel	2014	Effect of Chia (Salvia hispanica L) Addition on the Quality of Gluten-Free Bread	A	Journal of Food Quality	10.1111/jfq.12098
Zettel, V., Krämer, A., Hecker, F., & Hitzmann, B.	2014	Einsatz von Chiagelen in Weizenbroten.	A	brot+backwaren	http://www.brotundbackwaren.de/files/f2m-media/pdf/archiv/epaper/bub/2014/683kh73x/bub_2014-06_42_Einsatz_von_Chiagelen_in_Weizenbroten.pdf
Ayerza, Ricardo	2013	Seed composition of two chia (Salvia hispanica L.) genotypes which differ in seed color	A	Emirates Journal of Food and Agriculture	10.9755/ejfa.v25i7.13569
Estefanía N. Guiotto; Mabel C. Tomás; Susana M. Nolasco; Vanesa Y. Ixtaina	2013	Moisture-Dependent Engineering Properties of Chia (Salvia hispanica L.) Seeds	i. B.	Food Industry (978-953-51-0911-2)	10.5772/53173
Capitani, Marianela I.; Ixtaina, Vanesa Y.; Nolasco, Susana M.; Tomás, Mabel C.	2013	Microstructure, chemical composition and mucilage exudation of chia (Salvia hispanica L.) nutlets from Argentina	A	Journal of the Science of Food and Agriculture	10.1002/jsfa.6327
Ladio, Ana H.	2013	The Dynamics of Use of Nontraditional Ethnobiological Products: Some Aspects of Study	A	Methods and Techniques in Ethnobiology and Ethnoecology	10.1007/978-1-4614-8636-7_19
Coates, Wayne	2013	Chapter 16: ALA Sources - Plants, Seeds, and Nuts	i. B.	Omega-6/3 Fatty Acids	10.1007/978-1-62703-215-5_16
Iglesias-Puig, Esther; Haros, Monika	2013	Evaluation of performance of dough and bread incorporating chia (Salvia hispanica L.)	A	Eur Food Res Technol (European Food Research and Technology)	10.1007/s00217-013-2067-x
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