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Microbial transglutaminase in noodle and pasta processing

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ABSTRACT

Nowadays, there is an aggressive rate in consumption of noodles and pasta products throughout the world. Consumer acceptability and preference of these functional products can be promoted by the discovery of novel knowledge to improve their formulation and quality. The development of fortified-formulations for noodles and pasta products based on microbial transglutaminase (MTGase) can guarantee the shelf life extension with minimum quality losses. The current review focuses on recent trends and future prospects of MTGase utilization in the structural matrix of noodles and pasta products and represents the quality changes of cooking loss, texture, microstructure, color and sensory attributes of the MTGase-incorporated products. Digestibility, nutritional and health aspects of the MTGase-enriched formulations are also reviewed with a vision toward physical functions and safety outcomes of MTGases isolated from new microbial sources. The high potential of MTGase in developing commercial noodles and pasta products is successfully demonstrated. MTGase by modifying the crystallinity or molecular structure via covalent crosslinks between protein molecules strengthens the doughs stability and the textural characteristics of final products with the low- or high-protein flour. Compared with the control samples, the MTGase-supplemented products indicate slower digestion rates and better sensory and cooking properties without any remarkable color instability.

KEYWORDS

Transglutaminase; Noodle dough; Spaghetti; Gluten-free; Quality; Texture

Introduction

In recent years, noodle and pasta products have considered as one of the most important staple foods for a large part of the world's population. Based on the released data by world instant noodle association in 2015, China/Hong Kong, Indonesia, Japan, Viet Nam and the United States were the largest consumers of noodles (69.7% of total world consumption) (WINA 2016a). On the other hand, Italy, the United States, Turkey, Brazil, Russia and Iran respectively were the major producers of pasta (~9,410,078 tons) in 2015 (UNAFPA 2016). Increasing the production and consumption rate of these strategic products can be attributed to the simplicity in transportation, cooking, preparation, production mechanization and infrastructure development (Li et al. 2014b).

In parallel with further development and diversity of these wheat-based functional products in the industrial scale, use of particular reinforcing compounds (e.g., natural and chemical additives) and pre-treatments (e.g., hydrothermal, fermentation, and enzymatic) could substantially improve the dough rheological characteristics and the physicochemical quality of final products (Gulia et al. 2014). Meanwhile, the enzymatic treatments (with lipases, amylases, oxidoreductase and transglutaminase (TGase)) as sustainable and revolutionary bioprocessing solutions can deliver whole-grain cereal products with attractive sensory attributes and a decreased quantity of chemical agents (Niu et al. 2017).

TGase is extensively found in many mammalian, invertebrate and plant tissues and microbial cells (Kieliszek and Misiewicz 2014). This enzyme induces covalent crosslinks between two amino-acid residues of glutamine and lysine by the catalysis reaction of acyl transfer, without any limiting effect on the bioavailability of essential amino acid of lysine (Seguro et al. 1996; Li et al. 2014b). Seguro et al. (1996) after feeding TGase-treated proteins to rats demonstrated that lysine would be available for protein metabolism. Raczynski et al. (1975) from *in vivo* studies on rats found that the crosslinked structure (ϵ -(γ -L-glutamyl)-L-[14C]lysine) by TGase can be absorbed in the small intestine and that the 14C of the lysine was incorporated into plasma proteins. Fink and Folk (1981) also realized that ϵ -(γ -glutamyl)-Lysine isopeptides obtained by TGase function are an accessible substrate for the γ -glutamyl aminocyclotransferase (E.C. 2.3.2.4) of kidneys. Therefore, TGase by polymerizing proteins (e.g., gliadins and high-molecular-weight (HMW) glutenins in wheat) via the formation of these intermolecular crosslinks can successfully develop the texturized products with strong protein structure and extraordinary functional properties; such as enhanced dough strength and elasticity, water-holding capacity (WHC), and thermal stability (Gaspar and de Góes-Favoni 2015).

There is a high number of review articles published in the field of TGase role in the texturization and functionality modification of food-grade proteins for food applications (Kuraishi



et al. 2001; DeJong and Koppelman 2002; Jaros et al. 2006; Lee and Chin 2010; Kieliszek and Misiewicz 2014; Gaspar and de Góes-Favoni 2015; Santhi et al. 2017). Although use of this functional enzyme on the quality improvement of dairy (Jaros et al. 2006) and meat (Santhi et al. 2017) products has been comprehensively reviewed, there is no specific review in relation to the effect of TGase on the quality of wheat-based products. Moreover, to the best of our knowledge, no effort has been made so far to compile an updated and comprehensive review in the field of recent developments of noodles and pasta products texturized by TGase. Consequently, the current state-of-the-art potentials of this functional enzyme in the improving physicochemical, textural, microstructural, color, sensorial and nutritional quality properties of noodles and pasta products will be displayed.

Noodle and pasta: Main differences in formulation and processing

Table 1 reveals the differences present in formulation and processing of noodle and pasta products. The unleavened doughs to prepare noodle and pasta are mainly based on

common and durum wheat flours, respectively. Although flour of whole wheat and buckwheat is also used to formulate pasta products, a more diversity in flour used to prepare noodle dough (e.g., buckwheat, rice, oat, pea, mungbean, lupin, acorn, corn, etc) is observed. As pasta doughs are composed of semolina, their hardness and elasticity amounts are more than those of noodle doughs made of common wheat flours. Noodles are usually prepared in different forms of fresh, dried, deep-fried, parboiled, and steamed with a light color, while pasta products are only produced in two types of fresh and dried with an intense golden color. Overall, salt is a main ingredient in formulation of noodle, while diverse products of pasta usually are salt-free. The addition of 2–3% salt to Asian noodles can significantly improve the noodle texture by strengthening the gluten structure to increase viscoelasticity (Hou 2001). Egg is also considered as an essential component in processing noodles and fresh pastas. Even so, there are no egg solids in the composition of dried pastas. Also, there is no considerable variation in the received calorie quantities between noodle and pasta. Cooking process for noodles is faster than pasta products and typically served in a cold/hot seasonal broth (Table 1).

Table 1. The main differences between noodle and pasta.

Differentiating factor	Noodle	Pasta
Origin	Asia	Europe, Arabia
Definition	Prepared from unleavened dough and cooked in boiling water	Made of unleavened dough, wheat, buckwheat and water
Usual flours	Wheat, buckwheat, rice, mungbean, lupin, acorn, corn, potato, canna starch	Durum wheat, whole wheat, buckwheat
Wheat flour type	Common	Durum (semolina)
Salt in formulation	(+)	Mostly salt-free (-)
Egg in formulation	No less than 5.5% egg solids	Dried (-), Fresh (+)
Texture/Structure	Softer/Smooth, silky	Harder/Strong, elastic
Color	Lighter	More golden
Calories	Higher; ~138 (per 100 g)	Lower; ~131 (per 100 g)
Cooking speed	Quick	Slow
Serving traditional conditions	In a hot or cold seasonal broth	Addition of a sauce (after boiling)
Product type for sale	Fresh, dried, deep-fried, parboiled, steamed	Fresh, dried
Shopping cost	Cheap	Can be expensive
Product shape	Thin rod	Thin rod, tubes, or cylinders (spaghetti and macaroni), sheets (lasagna), swirls (fusilli)
Manufacturing technology	“Sheeting or roll-and-cut” process	“Extrusion” process
Technology simple illustration		

Products illustration



There is an obvious variance in production technology of noodles and pastas. Noodles and pastas are respectively produced by “sheeting or roll-and-cut” and “extrusion” processes (Table 1). Noodle products obtained by sheeting and cutting rolls are in form of thin rod, while pasta products produced during extrusion process have many forms; such as cylinders (spaghetti and macaroni), sheets (lasagna), swirls (fusilli), tubes and thin rod (Table 1).

For the preparation of instant noodles, the salt, egg, starch, flavoring agents, and other ingredients (with the exception of flour) in water are dissolved using a mixer. After adding the resulted mixture to the flour, a rest time is required to the dough maturity/development. After this step, the matured dough is kneaded to evenly distribute the imparted constituents and to wholly hydrate all the flour particles. To develop noodle strands with defined sizes, the obtained dough is then passed through rotating rollers to prepare two noodle sheets and then combined into a single sheet. The noodle sheet can similarly go through the rollers to fold again. This additional step can contribute to more develop the gluten network and the chewy texture in noodles (Hou and Kruk 1998; Fu 2008). A rotating slitter immediately can cut noodle strands of ideal width. The existence of some metal blocks/weights on the conveyor belt before the slitter can provide a wavy appearance for noodle strands. The noodle-strands are transferred to a steamer (90–100 °C for 1–5 min) with the aim of the cooking, starch gelatination and fixation of noodle waves. Sometimes, the steamed noodles prior to drying step into a dipping bath are immersed in liquid seasoning. This step can be removed by adding seasonings to the noodle strands before cutting and molding into the blocks (Hou and Kruk 1998; Gulia et al. 2014). Drying is the following stage in the noodle processing which can be implemented in two ways: (i) frying in oil (instant fried noodles) and (ii) drying with hot air (instant dried noodles). Both processes of frying (140–160°C for 1–2 min) or

hot-air drying (HAD, 70–90°C for 30–40 min) not only lead to more cook the product but also facilitate the starch gelatination and formation of an extremely porous and open structure to increase the rehydration rate (Gatade and Sahoo 2015). Under the above operating conditions, the moisture content in HAD is reduced from 30–50% at the steaming phase to 8–12%, while the fried noodles show a moisture reduction by 2–5% (Hou and Kruk 1998; Gulia et al. 2014). Generally, the frying is a better method compared to the HAD to produce instant noodles. This fact can be attributed to the irregular hot-air distribution on the noodle surface and its subsequent undesirable effects on the texture of the final product, longer cooking time and more reduction of the flavor sensory attribute (Gulia et al. 2014). In addition, use of edible oils with low amounts of unsaturated fatty acids and also strong antioxidants can significantly extend the shelf life of fried noodles by decreasing their oxidation rate (Lim et al. 2017). The dried samples after the drying step (HAD/frying) are finally cooled to pack into a bowl or a cup containing a hot vegetable soup or seasonings. In an industrial scale, products are spontaneously excluded from the assembly line after the cooling stage if a metal material is identified or their weight is out of the pre-set range. The industrial production process of instant noodles is depicted in Fig. 1.

For the pasta production, several key processing steps including mixing, kneading/extrusion, drying, and packaging are involved. Mixing stage is performed to prepare the pasta dough mixture with a moisture content of ~30% by blending pre-assessed ratios of durum wheat flour (semolina), some pseudo-cereal flours, water, egg emulsion (in some cases) and other components for 12–15 min into a mixer. However, the main function of in this phase is to uniformly distribute water among semolina particles and also to limit the formation of particle aggregates (Dalbon et al. 1996). This step can be under the vacuum in a continuous press because the air existence in dough pasta not only can provide a white, chalky appearance

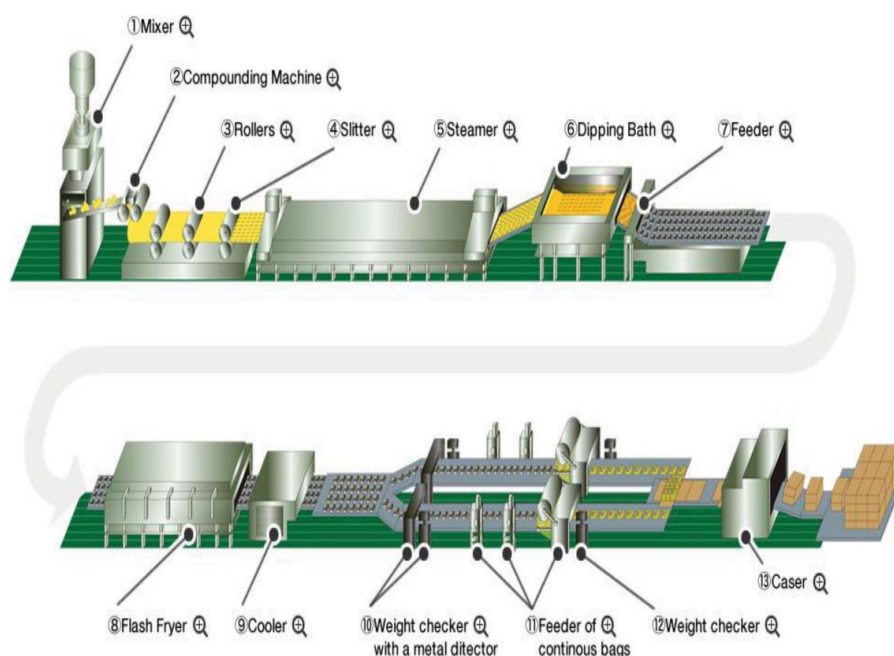


Figure 1. The production process of instant noodles. Permitted to reproduce from WINA (2016b).

but also can significantly alleviate the mechanical resistance of finished pasta (Icard-Verniere and Feillet 1999). An extruder system is applied to develop pasta products by the implementing stages of kneading and shaping. The kneading stage is usually implemented under vacuum to produce resistant doughs with even distribution of gluten and moisture and without any air bubbles. Thus, this step is an important process to reach a constant textural and color property in the final product (Feillet and Dexter 1996). Most presses have kneading perforated metal plates of at the end of the screw. Perforated metal plates mainly knead the dough into small-size streams and then mix them again on the other side of the plate to avoid inequalities of the pasta doughs. The gluten matrix after passing through these plates is much more continuous and starch granules are obviously aligned along the direction of flow (Harper and Clark 1979). This basic operation usually is associated with heat generation. For this reason, there is a water-cooling jacket in surrounding of extrusion cylinders in order to maintain interior temperature (45–50°C) of the extruder (Mariotti et al. 2011). Drying is considered as the last processing step for industrially producing pasta products with an extended shelf life. This process at both relatively low (60–70°C for 10–15 h) and high (60–120°C for 2–10 h) temperatures reduces the RH of the unleavened pasta doughs from 32–35% to less than 12.5% (Cubadda et al. 2007; Piwińska et al. 2016). However, advancement of drying systems is very imperative to achieve the effective heat and mass transfer coefficients (Li et al. 2014b).

New microbial sources of TGase

Several new microbial sources to produce TGases with their isolation origins and enzyme activities in the diverse fermentation modes are represented in Table 2. The maximum (4.3 U/mL) and minimum (0.2 U/mL) enzyme activities among the investigated strains were for TGases of *Streptomyces mobaraense* DSM 40587 (Zhang et al. 2012a) and *Streptomyces* sp. polar strains (Bahrim et al. 2010), respectively. Microbial TGase (MTGase) biosynthesized by *Streptomyces* sp. CBMAI 837 (4.18 U/mL), *S. hygroscopicus* WSH 03-01 (3.2 U/mL), *S. mobaraense* CECT 3230 (2.95 U/mL), and *Bacillus circulans*

BL32 (2.55 U/mL) also showed the high activities after the purification steps (Table 2). Generally, the main sources for MTGases considered strains of *Bacillus*, *Streptomyces*, *Enterobacter*, *Providencia* and Actinomycete. Although fed-batch submerged and solid state fermentations have been utilized to synthesize TGase from *S. hygroscopicus* WSH 03-01, MTGases extraction was mainly done in an Erlenmeyer flask system (Table 2). This fact demonstrates a special attention should be paid to design and develop fermentation systems in terms of novel bioreactors for enhancing the production yield and activity of MTGases.

Structural functions and safety issues of MTGase

An acyl transfer reaction is catalyzed by TGase or glutaminyl-peptide-amine γ -glutamyl transferase (EC 2.3.2.13) between a γ -carboxamide group in protein-bound glutamine residues (acyl donor) and an ϵ -amino group in a protein-bound lysine residue (acyl acceptor) to create covalent crosslinks of inter- or intramolecular ϵ -(γ -glutamine)-lysine isopeptidic bonds (Folk and Finlayson 1977). Formation of the polymerized protein matrix (10^6 – 10^7 g/mol) as a result of covalent bonds supports an opportunity to stabilize pharmaceutical/food-grade gels by changing surface hydrophobicity of protein molecules (Damodaran and Agyare 2013; Gaspar and de Góes-Favoni 2015). It has been proved that water in case of absence of lysine residues, free lysine unit and/or primary amine groups can play a key role in accepting the acyl group. The glutamine residues under this condition are hydrolytically deamidated and accordingly the acyl unit is transformed into glutamic acid. This biochemical reaction is adequate to vary the surface charge of proteins and their solubility amount (De Jong and Koppelman 2002). A modification in solubility rate can meaningfully adjust other functionalities in terms of gelation, thickening, WHC, emulsification and foaming mechanisms (Gaspar and de Góes-Favoni 2015).

Although there are conflicting issues in the field of MTGase safety, the FDA has approved this enzyme with No. GRN 000095 as “Generally Recognized as Safe (GRAS)” since 1998 (FDA 2001). MTGase has also affirmed in the US, Japan and

Table 2. Some new microbial sources producing TGase.

Microorganisms	Bacterial origin	Cultivation system	Activity (U/mL)	References
<i>Bacillus circulans</i> BL32	Aquatic environment (Amazon basin region, Brazil)	Erlenmeyer flasks	2.55	de Souza et al. (2011)
<i>Bacillus circulans</i> BL32	Aquatic environment (Amazon basin region, Brazil)	Erlenmeyer flasks	0.306	de Souza et al. (2006)
Actinomycete strains	Soil samples (Alexandria Governorate, Egypt)	Erlenmeyer flasks	~0.04	Eshra et al. (2015)
<i>Streptomyces</i> sp. polar strains	Antarctic soils	Erlenmeyer flasks	0.20 ^a	Bahrim et al. (2010)
<i>Streptomyces</i> sp. CBMAI 837	Brazilian soil	Erlenmeyer flasks	4.18 ^b	Macedo et al. (2011)
<i>S. hygroscopicus</i> WSH 03-01	Soil samples (China)	Solid state	1.74	Chen et al. (2013)
<i>S. hygroscopicus</i> WSH 03-01	Soil samples (China)	Fed-batch	3.2	Aidaros et al. (2011)
<i>S. mobaraensis</i> TX	Soil samples (China)	Erlenmeyer flasks	39.2 ^b	Jin et al. (2016)
<i>S. mobaraensis</i> DSM 40587	—	Erlenmeyer flasks	4.3	Zhang et al. (2012a)
<i>S. mobaraensis</i> DSM 40587	—	Erlenmeyer flasks	17.2 ^b	Zhang et al. (2012b)
<i>S. mobaraense</i> DSM 40847	Floating-floc/wastewater (Tuna canning factory, Thailand)	Erlenmeyer flasks	0.32–0.63	Bourneow et al. (2012)
<i>S. mobaraense</i> CECT 3230	—	Erlenmeyer flasks	2.95	Guerra-Rodríguez and Vázquez (2014)
<i>Enterobacter</i> sp. C2361	Wastewater of surimi industry (Songkhla, Thailand)	Erlenmeyer flasks	1.18	H-Kittikun et al. (2012)
<i>E. siamensis</i> sp. nov.	Seafood processing wastewater (Songkhla, Thailand)	—	—	Khunthongpan et al. (2013)
<i>Providencia</i> sp. C1112	Wastewater of surimi industry (Songkhla, Thailand)	Erlenmeyer flasks	1.78	H-Kittikun et al. (2012)

^aReported for the best strain coded as MIUG 13P.

^bReported as specific activity (U/mg).

Europe as a safe component in food processing (Gerrard et al. 2000). On 24 Nov. 2007, an Interim Marketing Authorization (IMA) in Canada was published to utilize MTGase at certain levels in formulation of different pre-wrapped poultry products and solid cut meats in the presence and absence of phosphate salts. The evaluated amounts were in accordance with the standard of Good Manufacturing Practice (Health Canada 2016).

Effect of MTGs addition on the quality properties

Physical characteristics

Changes of the physical properties (e.g., density, thickness, appearance, adhesiveness/stickiness, total organic matter (TOM), cooking loss/yield, and fat and water uptake) of noodles and pasta products as affected by the MTGase addition are indicated in Table 3. The MTGase addition led to a significant increase in dough density of fresh yellow alkaline noodle because of cross-linking enhancement within the protein network (Bellido and Hatcher 2010). Although Yeoh et al. (2014) showed that canned yellow alkaline noodles based on soy protein isolate (SPI) and MTGase had the lowest thickness value, a rise in MTGase concentration from 0 to 0.6% did not significantly affect the thickness of white salted noodles made from Korean wheat cultivars (Kang et al. 2014). Li et al. (2013) pointed out that the MTGase supplementation of capsaicin-enriched layered noodles did not affect the appearance. There was no significant difference in stickiness levels between the Moringa leaves powder-enriched noodles incorporated with MTGase and control samples (Limroongreungrat et al., 2011). The MTGase decreased stickiness amount of gluten-free hydroxy propyl methyl cellulose (HPMC) based pasta (Shokri et al. 2017); while the MTGase incorporation at concentration of 0.4% increased the stickiness quantity of bran supplemented spaghetti (Basman et al. 2006).

The TOM analysis demonstrated that the MTGase can significantly decrease its amount in rice and corn noodles (Yalcin and Basman 2008a,b), and bran supplemented spaghetti (Basman et al. 2006). The robust covalent crosslinks created by MTGase can be a dependable explanation for the decrement of TOM content. This formed network matrix limits the migration of starch granules during cooking process by their covering into a firm molecular package (Yalcin and Basman 2008a). Rosa-Sibakov et al. (2016) reported that there was no cooking loss for gluten-free pastas based on faba bean flour (FBF)-MTGase or starch-FBF-MTGase in comparison to the MTGase-free samples. Adding the MTGase remarkably attenuated cooking loss rate of dried white salted noodles (Wu and Corke 2005), gluten-free pea flour noodles (Takács et al. 2007), wheat-based pasta products (Takács et al. 2008), rice noodles (Yalcin and Basman 2008a), corn noodles (Yalcin and Basman 2008b), vital wheat gluten (VWG)/egg albumin-oat flour based noodles (Wang et al. 2011), gluten-free rice noodles (Kim et al. 2014), milled lupin flour/bran based-noodles (Bilgiçli and İbanoğlu 2015), and gluten-free HPMC based pasta (Shokri et al. 2017). SPI-yellow alkaline noodles supplemented with MTGase also had the lowest rate of cooking loss among all the investigated samples (Foo et al. 2011; Yeoh et al. 2014). High number of protein cross-links formed by MTGases can significantly provide a strong structural network and physical barrier

to prevent the water penetration and accordingly to reduce the cooking loss rate (Kim et al. 2014). However, in the other studies, there were no substantial alterations in the cooking yield between the control samples and, spaghetti and white salted-, whole wheat-, and Moringa leaves powder-enriched-noodles formulated with MTGase (Aalami and Leelavathi 2008; Limroongreungrat et al. 2011; Kang et al. 2014; Niu et al. 2017). In contrast, the MTGase incorporation into formulation of raw, dried and cooked noodles (Shiau and Chang 2013), and fibre-enriched spaghettis (Sissons et al. 2010) caused a more cooking loss than the control. These results were unfavorable for the developed products because of leaching out of the starch granules and other solid constituents as a result of the structure breakdown (Kim et al. 2014). Therefore, protein cross-linking formed by MTGase possibly reduced the protein-starch interactions and led to an increase in release rate of starch and non-starch constituents into the cooking water (Shiau and Chang 2013).

A lengthy shelf life can be guaranteed by lessening the uptake and rancidity of fat/oil. Having quickly removed water molecules in this processing stage, a number of small holes are formed on the product surface areas and followed by oil used to be filled (Ziaifar et al. 2008). Choy et al. (2010) found that the instant fried noodles supplemented with 1% MTGase (23.6%) had lower fat uptake compared to those were formulated without MTGase (29.8%). Although the addition of MTGase to formulation of rice- and white salted-noodles did not show a notable effect on their water uptake and swelling rates (Yalcin and Basman 2008a; Kang et al. 2014), a high water uptake rate was monitored for wheat-based pasta (Takács et al. 2008) and gluten-free pea flour noodle (Takács et al. 2007) by adding MTGase. However, Sissons et al. (2010) reported that the water uptake of fibre-enriched spaghetti can be diminished at MTGase concentrations more than 0.05%.

Chemical characteristics

Table 3 also shows the effect of MTGase addition on chemical properties (e.g., pH, free-amino acid groups, unextractable glutenin and salt-soluble protein and essential minerals) of noodles and pasta products. The formulation and treatment of noodles and pasta products mainly affect their pH values. An inverse relationship was observed between the pH amount and MTGase supplementation because of moderately acidic nature of the enzyme (Gan et al. 2009; Foo et al. 2011; Yeoh et al. 2014). Yeoh et al. (2011) represented a moderate pH for fresh SPI-yellow alkaline noodle. pH 7.4 was also determined as an optimum pH to attain the maximum capsaicin-retaining ability in chili powder-enriched layered noodles (Li et al. 2014b). The content of free amino acid can assess modification rate of proteins by MTGase. Wang et al. (2011) demonstrated that the oat noodle doughs formulated with VWG had the lower quantity of free-amino groups at high MTGase concentrations. This fact shows that the free amino groups of VWG have been consumed during the protein cross-linking reaction. Although the MTGase reduced the amount of salt soluble protein fractions in gluten-free pea flour noodles (Takács et al. 2007), a considerable rise in content of unextractable glutenin was observed with the MTGase incorporation into Chinese-style noodles (Bellido and Hatcher 2011). MTGase also has a potential to maintain

Table 3. Effect of MTGase on the physicochemical attributes of different noodle and pasta types.

Noodles and pasta products	Special mention of evaluated physical properties	Special mention of evaluated chemical properties	References
Fresh yellow alkaline noodle	A denser matrix for noodle dough was obtained with MTGase.	NR ^a	Bellido and Hatcher (2010)
Fresh SPI-yellow alkaline noodle	A notable improvement in physical properties of cooked noodles formulated with MTGase was monitored.	The pH value for MTGase-noodles was moderate.	Yeoh et al. (2011)
Canned SPI-yellow alkaline noodle	SPI-MTGase had the lowest retort cooking loss and thickness.	pH of thermally treated noodles was less than that of untreated-ones. pH amounts of all samples declined by retort processing.	Yeoh et al. (2014)
SPI-Yellow alkaline noodle	The lowest cooking yield was for SPI-MTGase noodle.	A notable decrease in pH was found with the addition of MTGase.	Foo et al. (2011)
Yellow SPI-noodle	NR	A drop from the original pH was found by adding MTGase to SPI-based noodle formulation.	Gan et al. (2009)
Instant fried noodle	The fat uptake of noodle formulated with 1.0% MTGase was lower than that of the control sample.	The extractability of proteins decreased by increasing alkali level up to 1.0%.	Choy et al. (2010)
Fried instant buckwheat noodle	MTGase decreased time of steaming and rehydration and the oil concentration in formulations.	NR	Li et al. (2008)
Rice noodle	The cooking loss (~55%) and water turbidity (~67%) decreased after treating noodles with MTGase and rice protein isolate.	NR	Kim et al. (2014)
Rice noodle	MTGase had not a significant effect on the cooking loss, water absorption and swelling rates. Cooking loss of the MTGase-incorporated samples was significantly less than those of the control. The total organic matter significantly decreased with the MTGase addition.	NR	Yalcin and Basman (2008a)
Oat flour-based noodle	1.0% MTGase addition to noodles containing gluten or egg albumin decreased the cooking loss rate.	The free amino groups number changed based on the interaction of protein cross-linking of MTGase.	Wang et al. (2011)
Corn noodle	Use of MTGase provided a final product with smooth surface along with a reduction in cooking loss and total organic matter amounts.	NR	Yalcin and Basman (2008b)
White salted noodle	An increase in MTGase level did not change water absorption and thickness amounts of the noodle dough sheet and also cooking loss rate.	NR	Kang et al. (2014)
Dried white salted noodle	A significant decrease in cooking yield was obtained by adding MTGase.	NR	Wu and Corke (2005)
Whole-wheat noodle	There was no significant difference for cooking yield between samples formulated with MTGase and control.	NR	Niu et al. (2017)
Chinese-style noodle	MTGase addition led to a substantial improvement in physical properties via the formation of ϵ -(γ -glutamyl) lysine.	NR ^a	Sakamoto et al. (1996)
Noodles and pasta products	Special mention of evaluated physical properties	Special mention of evaluated chemical properties	References
Chinese-style noodle	MTGase addition led to a substantial improvement in physical properties via the formation of ϵ -(γ -glutamyl) lysine.	NR ^a	Sakamoto et al. (1996)
Chinese-style noodle	NR	A significant increase in unextractable glutenin content by supplementing MTGase was found.	Bellido and Hatcher (2011)
Milled lupin flour/bran based-noodle	MTGase application decreased the cooking loss levels	Essential mineral levels were improved by increasing ratio of lupin flour (10-30%) and bran (10-20%) in the presence of MTGase.	Bilgiçli and İbanoğlu (2015)
Gluten-free pea flour noodle	A high rate in water uptake and a low cooking loss were found by supplementing MTGase.	A significant decrease in the water content and salt-soluble protein fractions and a change in molecular weight distributions were found by adding 50–200 mg/kg MTGase.	Takács et al. (2007)
Capsaicin-enriched layered noodle	MTGase-incorporated noodles compared with the control had a more slippery on the surface.	The capsaicin release rate in simulated gastrointestinal conditions decreased by increasing MTGase concentration.	Li et al. (2013)
Chili powder-enriched layered noodle	Appearance of the control and MTGase-supplemented noodles was similar.	Wheat flour-SPI based noodles containing MTGase had the highest retentive capacity of capsaicin at pH 7.4. The capsaicin-retaining ability at pH 1.2 was similar for all noodles.	Li et al. (2014)
Moringa leaves powder-enriched noodle	There were no significant differences in cooking loss and adhesiveness amounts by the adding MTGase.	NR	Limroongreungrat et al. (2011)

(Continued on next page)

Table 3. (Continued)

Noodles and pasta products	Special mention of evaluated physical properties	Special mention of evaluated chemical properties	References
Noodle (raw, dried and cooked)	A lower cooking loss (4.98%) for control noodle was determined compared with that of noodles containing MTGase (5.84–6.12%). Moisture content of cooked noodle formulated with MTGase (0.5–1.5%) was significantly lower than that of the control.	NR	Shiau and Chang (2013)
Wheat-based pasta	MTGase-incorporated pastas compared to the untreated ones had good cooking quality with high water uptake and low cooking loss.	Quantities of protein fractions of water/salt-, the alcohol- and the alkali-soluble were decreased by increasing 10–200 mg/kg.	Takács et al. (2008)
Pseudo-cereals based pasta	The use of MTGase (50–200 mg/kg) led to products with excellent cooking quality.	MTGase notably decreased the quantities of low-molecular weight fractions and soluble protein ones.	Kovács (2003)
Gluten-free faba bean pasta	No cooking loss for faba-MTGase or starch-faba-MTGase samples compared to the pastas without MTGase is found. MTGase addition avoided the swollen of starch granules.	In fermented faba pasta, MTGase possibly could not form covalent crosslinks between protein chains.	Rosa-Sibakov et al. (2016)
Gluten-free HPMC based pasta	MTGase decreased cooking loss and stickiness of pasta. MTGase had no significant effect on the moisture content.	NR	Shokri et al. (2017)
Spaghetti	Cooking loss of spaghetti supplemented with 0.5% and 1.0% MTGase was slightly lower than that of the control.	A considerable reduction in amount of ~66 kDa bands was observed.	Aalami and Leelavathi (2008)
Bran supplemented spaghetti	MTGase addition, particularly at the level of 0.4%, led to an increase in stickiness amounts. MTGase supplementation led to a significant decrease in contents of total organic matter of the bran supplemented samples	NR	Basman et al. (2006)
Fibre-enriched spaghetti	MTGase enhanced cooking loss but there was no effect of MTGase content. The water absorption was decreased at MTGase > 0.05%.	NR	Sissons et al. (2010)

^aNR = not reported.

essential minerals in noodles composed of milled lupin products (flour and bran) (Bilgiçli and İbanoğlu 2015).

Textural/mechanical characteristics

Table 4 summarizes the product textural/mechanical and dough rheological properties of noodles and pastas as affected by the MTGase inclusion. In general, the use of MTGase in noodles and pasta products could considerably increase values of the textural characteristics. These critical attributes also could be improved with an increase in concentration of MTGase. The tensile or breaking strength of fresh SPI-yellow alkaline noodles (~75–100 kPa), yellow SPI-noodles (~80–85 kPa), dried SPI-spaghetti (a little less than 230 gram-force (gf)), dried white salted noodles (9.6–14.3 gf), chili powder-enriched layered noodles (~80 kPa), Moringa leaves powder-enriched noodles (0.085–0.107 N), and raw, dried and cooked noodles (~3.2–5.0 N) improved with the MTGase (Wu and Corke 2005; Aalami and Leelavathi 2008; Gan et al. 2009; Limroongreungrat et al. 2011; Yeoh et al. 2011; Shiau and Chang 2013; Li et al. 2014). The elasticity enhancement with the MTGase supplementation was also reported by Li et al. (2008) for fried instant buckwheat noodle (33–43% increase rate), Gan et al. (2009) for yellow SPI-noodle (~50–55 kPa), Bellido and Hatcher (2011) for Chinese-style noodle (152–184 MPa by analyzing the loss modulus), Yeoh et al. (2011) for fresh SPI-yellow alkaline noodle (~50–65 kPa), Li et al. (2014) for chili powder-enriched layered noodle (~30 kPa), and Niu et al. (2017) for whole-wheat noodle (0.221–0.230 J/m³ based on the TPA (resilience) analysis). An improvement in the values of hardness

(Seo et al. 2003; Shin et al. 2005; Wu and Corke 2005; Li et al. 2008; Yalcin and Basman 2008b; Li et al. 2013; Niu et al. 2017), and firmness (Basman et al. 2006; Sissons et al. 2010; Limroongreungrat et al. 2011; Kang et al. 2014), chewiness (Seo et al. 2003; Shin et al. 2005; Li et al. 2008), springiness (Yeoh et al. 2011; Niu et al. 2017), gumminess (Seo et al. 2003; Wu and Corke 2005), adhesiveness (Li et al. 2008; Limroongreungrat et al. 2011), and cohesiveness (Li et al. 2008) for the different noodle/pasta formulations were reported by supplementing the MTGase.

The better-quality texture can be directly related to the decline of dough softening degree (Shokri et al. 2017), and improvement of dough mechanical strength (Bellido and Hatcher 2010; Sissons et al. 2010), stability (Seo et al. 2003; Shin et al. 2005; Niu et al. 2017; Shokri et al. 2017), and development time (Kim et al. 2014; Niu et al. 2017; Shokri et al. 2017). MTGase cross-linking reactions of heterogeneous proteins can significantly reinforce the texture through the formation of strong protein networks between the starch granules (Folk and Finlayson 1977). Some researchers analyzed the oscillatory rheological parameters (e.g., storage (G') and loss (G'') moduli) of noodle dough sheets and found that the MTGase incorporation can significantly improve their rheology (Wu and Corke 2005; Bellido and Hatcher, 2010; Wang et al. 2011; Kim et al. 2014). Increasing the G' and G'' amounts with increasing MTGase concentration may be attributed to the more cross-linking of MTGase between the additional residues of lysine and glutamine amino acids in the protein structure (Larre et al. 2000). Bellido and Hatcher (2010) utilized

Table 4. Effect of MTGase on the textural and structural characteristics of different noodle and pasta types.

Noodles and pasta products	Special mention of assessed textural/rheological properties	Special mention of assessed microstructural properties	References
Fresh yellow alkaline noodle	The mechanical strength of noodle dough was increased according to the changes of longitudinal mechanical moduli.	NR ^a	Bellido and Hatcher (2010)
Fresh SPI-yellow alkaline noodle	A maximum value for tensile strength and elasticity was recorded for the MTGase-supplemented noodles.	MTGase modified the crystallinity or molecular structure of the formed matrix.	Yeoh et al. (2011)
Canned SPI-yellow alkaline noodle	<ul style="list-style-type: none"> Retort processing led to a reduction in values of textural parameters 	Retort processing and storage reduced structural complexity in SPI-MTGase and SPI-ribose-MTGase	Yeoh et al. (2014)
SPI-Yellow alkaline noodle	<p>The highest values of textural parameters was for the SPI-MTGase</p> <p>SPI-MTGase noodle had the highest values of textural and mechanical characteristics</p>	The slowest breakdown rate with a highly-dense structure was for SPI/MTGase noodle because of the extra protein crosslinking.	Foo et al. (2011)
Yellow SPI-noodle	MTGase significantly increased tensile strength and elasticity.	NR	Gan et al. (2009)
Instant fried noodle	MTGase improved the textural characteristics of sample prepared with the low-protein flour.	The structural expansion within the noodle matrix was increased	Choy et al. (2010)
Fried instant buckwheat noodle	MTGase improved the elasticity, adhesiveness, hardness, cohesiveness, chewiness and fracture force.	NR	Li et al. (2008)
Rice noodle	MTGase enhanced the development time and maximum and peak torques of noodle dough.	A smooth surface was arisen in cracked noodle by the MTGase addition.	Kim et al. (2014)
Rice noodle	The maximum force was not affected by MTGase incorporation followed by a resting time (1-2 h) before drying	Rice noodle restructured with rice protein isolate and MTGase showed a smoother surface.	Yalcin and Basman (2008a)
Rice flour-based noodle	MTGase addition (3000-7000 ppm) to the dough increased its stability.	NR	Shin et al. (2005)
Corn noodle	<p>The chewiness and hardness values of noodles formulated with 30% rice flour were notably improved by adding 7000 ppm MTGase.</p> <p>MTGase addition after a 1-2 h resting period before drying significantly improved values of maximum force.</p>	The MTGase addition strengthened the noodle structure via covalent crosslinks between protein molecules	Yalcin and Basman (2008b)
White salted noodle	A larger elasticity and a firmer texture for noodles supplemented with 0.4% MTGase in comparison with the control were found.	Reinforcement the structural integrity was found using MTGase-catalyzed crosslinking.	Kang et al. (2014)
Dried white salted noodle	1.0 g/kg MTGase addition can increase the storage modulus and loss modulus of fresh dough sheets.	NR	Wu and Corke (2005)
Whole-wheat noodle	<p>Hardness, tensile force and gumminess of the dried samples were usually increased by adding MTGase.</p> <p>MTGase improved the development time and stability of whole-wheat dough of produced noodles.</p>	Forming the cross-links of ϵ -(γ -glutamyl) lysine by MTGase improved the network microstructure.	Niu et al. (2017)
Korean wheat flour-based noodle	MTGase enhanced the hardness, springiness and resilience or elasticity levels of cooked noodles.	MTGase increased the connectivity of gluten network and highly covered starch granules in the structure of developed noodles.	Seo et al. (2003)
Chinese-style noodle	The dough stability and noodle textural characters (gumminess, hardness, chewiness) were improved by the addition of MTGase.	Structural complexity and strong network formation was highly improved.	Sakamoto et al. (1996)
Chinese-style noodle	Breaking strength of pickled and retorted noodles increased by increasing MTGase level.	The MTGase treatment reinforced protein network in the noodle structure.	Yamazaki et al. (2004)
Chinese-style noodle	<p>The boiled noodles containing MTGase had a more breaking strength of than the control.</p> <p>The simultaneous adding of MTGase and protein degradation products compared to MTGase alone led to a more improvement in the mechanical properties.</p>	NR ^a	Yamazaki et al. (2004)
Chinese-style noodle	The boiled noodles containing MTGase after storing in a refrigerator significantly kept their mechanical/textural properties with time.	MTGase reinforcing effect (connectivity degree of the protein network) improved the protein layer thickness enveloping the starch granules.	Bellido and Hatcher (2011)
Gluten-free pea flour noodle	The mechanical behaviour showed a more elasticity and a meaningfully less viscous by incorporating MTGase.	MTGase could integrate fractions with low molecular weight (MW) into the developed protein structure forming new non-salt soluble high MW protein subunits.	Takács et al. (2007)

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Table 4. (Continued)

Noodles and pasta products	Special mention of assessed textural/rheological properties	Special mention of assessed microstructural properties	References
Capsaicin-enriched layered noodle	1.5% MTG supplemented noodles were the hardest and needed to a maximum force to chew. The hardness increased by enhancing MTGase content from 0.5 to 1.5%.	MTGase-supplemented noodles exhibited a denser structure than the control. A high denseness with a low void structure was observed at increased concentrations of MTGase.	Li et al. (2013)
Chili powder-enriched layered noodle	MTGase-supplemented noodles based on wheat flour-SPI had the maximum tensile strength and elasticity.	A substantial increase in covalent cross-linking between protein matrices with the presence of MTGase led to a structural integration and a slow diffusion rate for capsaicin.	Li et al. (2014)
Moringa leaves powder-enriched noodle	A significant increase in firmness and tensile strength values of cooked samples was found by increasing MTGase from 0 to 0.3%. Use of high content of MTG (0.5-0.9%) led to a decrease in textural parameters.	An improvement in network microstructure was obtained by adding MTGase to the formulation.	Limroongreungrat et al. (2011)
Noodle (raw, dried and cooked)	The cutting and breaking forces of raw and dried noodles considerably increased by increasing MTGase concentration. A significant increase in amounts of cutting force, tensile strength, and extensibility of cooked noodles was observed with an increase in MTGase level (0-1.5%).	NR	Shiau and Chang (2013)
Wheat-based pasta	NR	MTGase could modify the structure network of gluten in the final products.	Takács et al. (2008)
Gluten-free faba bean pasta	MTGase increased some textural parameters of faba bean flour-based pastas. MTGase had no significant effect on the texture of pasta formulated with fractionated or fermented faba.	The intermolecular crosslinks of MTGase changed the protein structure and improved the textural characteristics by entrapping starch in the formed protein network.	Rosa-Sibakov et al. (2016)
Noodles and pasta products	Special mention of assessed textural properties	Special mention of assessed microstructural properties	References
Gluten-free HPMC based pasta	The dough development time was increased, while a decrease in degree of dough softening was monitored. The dough stability time and water absorption were not significantly affected by MTGase.	NR	Shokri et al. (2017)
Spaghetti	A significant decrease in the solubility of semolina dough proteins and a considerable improvement in the final product were found by the MTGase addition.	The protein network in structure of pasta supplemented with MTGase was much tighter than that of the control.	Aalami and Leelavathi (2008)
Bran supplemented spaghetti	Firmness values respectively increased and decreased with increasing concentration of MTGase and bran.	MTGase-catalyzed crosslinking strengthens the structural integrity of spaghetti.	Basman et al. (2006)
Fibre-enriched spaghetti	The MTGase addition increased dough maximal resistance. 0.5% MTGase caused an optimum impact on dough strength and produced the firmest and least sticky pasta.	More extensive cross-links and thicker protein matrix were observed in the MTGase supplemented pasta.	Sissons et al. (2010)

^aNR = not reported.

low-intensity ultrasound as a suitable tool to identify the variations of dough mechanical characteristics of fresh yellow alkaline noodles. They demonstrated that the use of MTGase concentrations more than 2% in noodle formulation can be remarkably reduced and enhanced the attenuation and velocity of ultrasonic longitudinal waves, respectively. In addition, effects of cooking (Yeoh et al. 2011), and retort canning (Yeoh et al. 2014) on some textural characteristics of noodles and pasta products formulated with MTGase have been recently studied. These researchers concluded that the thermal processing can cause a noticeable reduction in values of textural properties and the structural integrity of SPI-yellow alkaline noodles. Increasing the moisture diffusion in terms of penetration of water molecules during heating can lead to the physico-chemical variations of proteins (the integrity reduction and

surface disruption) and starch granules (fast swelling, amylose leaching and gelatinization). Having gelatinized the starch granules, they were unable to reinforce the noodles elasticity and to reconstitute their mechanical energy. Therefore, the interior gel structure containing swollen granules gradually got softer by increasing the process time (Hatcher et al. 2009).

Microstructural characteristics

Many studies showed that the use of MTGase can pronouncedly improve the structural integrity and density and connectivity degree of protein matrixes through formation of the covalent cross-links of ϵ -(γ -glutamyl) lysine (Table 4). Entrapment of starch granules in the strong protein network formed by MTGase can provide a potential to more keep functional ingredients incorporated into the formulations of

noodle/pasta with a smoother surface (Bellido and Hatcher 2011; Yeoh et al. 2014; Susanna and Prabhasankar 2015; Niu et al. 2017). Wu and Corke (2005) also using a cross-sectional vision in microstructural analysis revealed a long 'channel' in the central zone of the dried white salted noodle after fracturing which was probably arisen during its dough folding. This 'channel' area could be considerably decreased by the supplementing MTGase. The MTGase inclusion into the noodle/pasta doughs can also stabilize the structural network against impacts of cooking and retort processing via enhancement of the isopeptidic bonds and development of a greater amount of orientation for the protein microfibrils and starch granules (Yeoh et al. 2011; Yeoh et al. 2014). MTGase compared with glucose oxidase and endoxylanase observed the densest and most condensed gluten structure in whole wheat-noodle which could remarkably increase the dough strength and mixing stability (Niu et al. 2017).

Color characteristics

The color attributes of noodles and pasta products were investigated in terms of L^* (brightness/lightness), a^* (redness), and b^* (yellowness) values. In general, there was not a marked trend for changes of L^* , a^* and b^* color values (Table 5). The color L^* value of fresh SPI-yellow alkaline noodle (Yeoh et al. 2011), white salted noodle (Kang et al. 2014), raw and cooked pasta (Susanna and Prabhasankar 2015), and whole-wheat noodle (Niu et al. 2017) was increased by adding the MTGase, while a significant decrease in L^* value was observed for yellow alkaline noodle (Foo et al. 2011), yellow SPI-noodle (Gan et al. 2009), dried white salted noodle (Wu and Corke 2005), chili powder-enriched layered noodle (Li et al. 2014), gluten-free faba bean pasta (Rosa-Sibakov et al. 2016), and spaghetti (Aalami and Leelavathi 2008). An enzymatic process between phenolic compounds and polyphenol oxidases under the certain reaction conditions (e.g., pH and ionic strength) is responsible for the product discoloration. Asenstorfer et al. (2009) reported that the addition of MTGase to the dough in different levels of pH and ionic strength led to a very slight change in color indexes. Therefore, the interaction of MTGase and phenolic constituents can reduce the discoloration rate by decreasing the contact level between the enzyme and substrate. The natural color (dark brown) of some used flours owing to the higher amount of ash and presence of outer layers can reduce the final product brightness by facilitating enzymatic and non-enzymatic (Maillard) browning reactions during the drying step (Ramli et al. 2009; Foo et al. 2011; Rosa-Sibakov et al. 2016). Nevertheless, decreasing the L^* value by supplementing MTGase in some noodle/pasta products can be owing to the ammonia release, its participation in the Maillard reaction and also flavones separation during the formation of covalent crosslinks between flour protein molecules (Miskelly 1984; Wu and Corke 2005).

There was a decrease in a^* color level for gluten-free faba bean pasta (Rosa-Sibakov et al. 2016), and spaghetti (Aalami and Leelavathi 2008) by the supplementing MTGase. The redness reduction may be because of the restricted levels of available lysine and thus Maillard reaction as a result of MTGase enzymatic actions (Aalami and Leelavathi 2008). The MTGase inclusion also increased this factor in a greater number of products; such as, canned SPI-yellow alkaline noodle (Yeoh et al.

2014), rice noodle (Yalcin and Basman 2008a), dried white salted noodle (Wu and Corke 2005), and chili powder-enriched layered noodle (Li et al. 2014). Although an increase in level of this color parameter was found in MTGase-supplemented dried white salted noodle (Wu and Corke 2005), spaghetti (Aalami and Leelavathi 2008), chili powder-enriched layered noodle (Li et al. 2014), canned SPI-yellow alkaline noodle (Yeoh et al. 2014), and gluten-free faba bean pasta (Rosa-Sibakov et al. 2016) formulated with the MTGase showed a decrease in b^* color index. Yellow color of alkaline noodles is due to the presence of high amounts of xanthophyll pigments and somewhat flavonoid components of apigenin-C-diglycosides in wheat flours, which naturally are colorless at acidic and neutral pHs. These compounds at alkaline pHs can be yellowish. Decrement of the color b^* value can be, however, related to the pH increase of the product because of leaching and the loss of alkaline salts into the water (Asenstorfer et al. 2006). Nonetheless, some other researchers found that there was no substantial difference in the color L^* , a^* and b^* values between the control and MTGase-supplemented products (Yalcin and Basman 2008b; Choy et al. 2010; Sissons et al. 2010; Limroongreungrat et al. 2011; Bilgiçli and İbanoglu 2015; Shokri et al. 2017).

Sensory characteristics

Results obtained from the sensory evaluation of noodles and pasta products indicated that the MTGase addition led to the significant improvement of sensory characteristics, so that these samples had the highest organoleptic scores in terms of appearance/surface smoothness (Takács et al. 2008; Yalcin and Basman 2008a; Li et al. 2013), bulkiness (Basman et al. 2006), texture (hardness (Yeoh et al. 2011; Rosa-Sibakov et al. 2016), firmness (Basman et al. 2006), springiness (Yeoh et al. 2011; Li et al. 2013; Niu et al. 2017), consistency (Takács et al. 2008), and chewiness (Yalcin and Basman 2008a; Rosa-Sibakov et al. 2016)), aroma/odor/taste (Takács et al. 2008; Li et al. 2013), and mouthfeel after chewing properties (Yalcin and Basman 2008a,b; Niu et al. 2017). In addition, some scholars only relied to express the improved sensory quality in rice flour-based noodles at 700 ppm MTGase (Shin et al. 2005), Korean wheat flour-based noodles at 3000–7000 ppm MTGase (Seo et al. 2003), gluten-free pea flour noodles at 140 ppm MTGase (Takács et al. 2007), pseudo-cereals based pastas at 100 ppm MTGase (Kovács 2003), Moringa leaves powder-enriched noodles at 0.3% MTGase (Limroongreungrat et al. 2011), and gluten-free 2% HPMC-based pastas at 0.7% MTGase (Shokri et al. 2017).

Texture and appearance are the most important sensory attributes, so that typical consumers would prefer products with desirable hardness and brightness without any discoloration (Hatcher and Anderson 2007). The improvements on the organoleptic characteristics by MTGase were positively associated to the alterations on the dough mixing and noodle texture (hardness and elasticity) properties (Yeoh et al. 2011). The high springiness level in samples supplemented with MTGase can be due to the more adhesion of starch granules via the modification of network structure provided by protein cross-links of MTGase (Choy et al. 2010). The decrease of smoothness and/or the increase of firmness in the control sample may be

Table 5. Effect of MTGase on the color and sensory attributes of different noodle and pasta types.

Noodles and pasta products	Special mention of determined color properties	Special mention of determined sensory properties	References
Fresh SPI-yellow alkaline noodle	SPI-MTGase noodle was significantly evaluated with maximum L* (brightness) value among all the samples.	MTGase-supplemented sample had the highest hardness and springiness amounts.	Yeoh et al. (2011)
Canned SPI-yellow alkaline noodle	The minimum yellowness was for SPI-MTGase. Retort processing led to an increase in a* (redness), and a decrease in b* (yellowness) levels.	NR ^a	Yeoh et al. (2014)
Yellow alkaline noodles	SPI/MTGase noodle revealed a lower L* value than the control and SPI ones.	NR	Foo et al. (2011)
Yellow SPI-noodle	SPI-ribose-MTGase noodles showed a less L* value compared with the control and SPI-MTGase noodles.	NR	Gan et al. (2009)
Instant fried noodle	There was no noticeable difference in the color between the different treatment blends.	NR	Choy et al. (2010)
Rice noodle	A marginal rise in a* value of samples incorporated with MTGase was obtained.	Addition of MTGase in samples formulated with xanthan gum led to a marginally more scores for the surface, chewing and mouthfeel after chewing attributes.	Yalcin and Basman (2008a)
Rice flour-based noodle	NR	The MTGase addition at 7000 ppm to the noodle dough promoted the sensory scores.	Shin et al. (2005)
Corn noodle	The color values of L*, a* and b* were slightly changed by the formulation supplementation with MTGase	The MTGase-supplemented noodles containing xanthan gum had higher mouthfeel after chewing properties.	Yalcin and Basman (2008b)
White salted noodle	L* value of the noodle dough sheet enhanced by adding MTGase concentration.	NR	Kang et al. (2014)
Dried white salted noodle	A marginal adverse effect on the color was resulted: I. A significant decrease in L* value was found by adding MTGase up to 10 g/kg. II. A significant increase in b* value was found with the addition of MTGase (1.0 g/kg).	NR	Wu and Corke (2005)
Whole-wheat noodle	MTGase increased the color quality of noodles by inhibition discoloration reaction	The enzyme promoted the sensory characters of noodles (e.g., mouth-feel, bite and springiness)	Niu et al. (2017)
Korean wheat flour-based noodle	NR	An increase from 3000 to 5000 ppm MTGase led to an improvement in sensory attributes.	Seo et al. (2003)
Milled lupin flour/bran based-noodle	The L*, a* and b* values of lupin flour and bran noodles were not changed by adding MTGase.	Raw and cooked noodles supplemented with MTGase with 10% lupin flour had the maximum sensory scores	Bilgiçli and İbanoğlu (2015)
Gluten-free pea flour noodle	NR ^a	Application of 140 mg/kg MTGase in the formulation resulted in the best sensory and cooking attributes.	Takács et al. (2007)
Capsaicin-enriched layered noodle	NR	All the characters (appearance, smoothness, odor, flavor and springiness) had a sensory score more than 5. The preference decreased by increasing MTGase level.	Li et al. (2013)
Chili powder-enriched layered noodle	The L* and b* values of the layered noodles were meaningfully lower than the commercial ones. a* value of all the prepared noodles was significantly more than the commercial ones.	NR	Li et al. (2014)
Moringa leaves powder-enriched noodle	The color values (L*, a*, b*) were not affected by the addition of MTGase.	The maximum score of overall acceptability belonged to noodles formulated with 0.3% MTGase.	Limroongreungrat et al. (2011)
Wheat-based pasta	NR ^a	Evaluating the organoleptic attributes (appearance, aroma, taste, consistency and weighted average) showed a significant improvement in the noodle quality with high water uptake and low cooking loss.	Takács et al. (2008)
Pseudo-cereals based pasta	NR ^a	The MTGase addition improved sensory attributes of pastas.	Kovács (2003)
Gluten-free faba bean pasta	MTGase addition decreased the values of L*, a* and b*. But these changes were not observable.	Fermentation process along with MTGase addition increased hardness and particularly chewiness.	Rosa-Sibakov et al. (2016)
Gluten-free HPMC based pasta	MTGase addition had no significant effect on the pasta color.	The pasta formulated with 2% HPMC and 0.7% MTGase had the highest sensory scores for texture and overall acceptability in comparison to the control.	Shokri et al. (2017)
Spaghetti	The MTGase addition significantly decreased L*, a* and b* values of the spaghetti surface.	NR	Aalami and Leelavathi (2008)

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Table 5. (Continued)

Noodles and pasta products	Special mention of determined color properties	Special mention of determined sensory properties	References
Bran supplemented spaghetti	NR	MTGase caused significantly higher sensory scores for firmness, stickiness, and bulkiness compared with the control samples.	Basman et al. (2006)
Fibre-enriched spaghetti	The L*, a* and b* values were not affected by MTGase.	NR	Sissons et al. (2010)

^aNR = not reported.

attributed to the presence of more number of swollen granules with a diffused gel structure on the product surface (Ross et al. 1997; Yeoh et al. 2011). In general, an optimal level for MTGase is needed to compress a noodle/pasta between the molars because many people especially the Asian consumers prefer softer noodles or pasta products. Therefore, attendance to an ideal concentration for MTGase in noodle/pasta dough formulation is necessary to have the best sensory characteristics in a commercial scale.

In vitro starch digestibility

Overall, the low amount of predicted glycemic index is suitable because it shows a gentler speed of carbohydrates digestion and a lesser insulin requirement. The existence of MTGase-induced protein cross-linking in chili powder-enriched layered noodles significantly reduced this index, so that a high retention of capsaicin in the enriched noodles was recorded due to their more resistance to digestion process (Li et al. 2014). This fact can be attributed to the limited activity of enzymes and the mobility reduction of sugar substances through encapsulation of starch granule cores into strong film layers (Rosa-Sibakov et al. 2016). Colonna et al. (1990) had earlier reported that proteins can successfully encapsulate starch granules to prevent the α -amylase accessibility. A low hydrolyzing rate for *in vitro* starch digestion was also monitored for the yellow SPI-noodle and gluten-free faba bean pasta supplemented by MTGase (Gan et al. 2009; Rosa-Sibakov et al. 2016). This MTGase action was similar to some indigestible polymers and non-fibrous substances which were able to prevent the starch digestion under *in vitro* and *in vivo* conditions (Granfeldt et al. 1992). Moreover, it was observed that high levels of resistant starch and dietary fiber (non-starch polysaccharides) had a synergistic effect on MTGase potential to alleviate glucose absorption rate in gastrointestinal tract (Ramli et al. 2009; Li et al. 2014). Mechanisms of resistant starch and dietary fiber to decrease the starch susceptibility to be enzymatically digested are aiding the starch escape digestion and the interim barrier formation in terms of sticky gels, respectively (Eerlingen and Delcour 1995; Chong and Aziz 2010).

Nutritional and health aspects

Enrichment of noodles and pasta products with nutritive ingredients such as flour of legumes and pseudo-cereals, the bran and germ of grains, essential minerals, vitamins, antioxidant and natural pigments, flavors, antimicrobial agents and essential oils can considerably enhance the nutritional quality of these strategic products (Basman et al. 2006; Gulia et al. 2014; Elobeid et al.

2014; Li et al. 2014b; Bilgiçli and İbanoğlu 2015; Piwińska et al. 2016; Sęczyk et al. 2016; Kazemi et al. 2017; Mridula et al. 2017; Shahsavani and Mostaghim 2017). Fortification can be usually carried out by direct adding the functional constituents to the used flours or liquid and powdered seasonings. Although the seasoning enrichment due to the exposure lack to environmental/processing conditions (heat and moisture) and also the improved protection in packaging systems is a suitable nutritional strategy, a large problem to apply this fortification way is the unreliability of physicochemical stability of added nutrients during the storage (Gulia et al. 2014). Use of MTGase in the consumed flour gives a possibility to form a stable polymeric matrix for encapsulating many functional compounds via the generation of intricate protein bonds. For example, the spaghetti supplementation with bran can lead to difficulties in its color and cooking quality because of this fiber-rich source attenuates the gluten matrix conjunction and the dough mechanical strength (Manthey and Schorno 2002). Basman et al. (2006) explained that the MTGase by changing the dough rheological behavior not only inhibits the protein network breakdown in the cooking operation, but also provides a healthy spaghetti with low surface stickiness by reducing the diffusion/release rate of secretions during gelatinization process of starch granules. Bilgiçli and İbanoğlu (2015) have recently reported that noodles fortified with 10–20% lupin bran can remarkably increase the content of minerals (Ca, Cu, Fe, Mg and Zn). Therefore, the existence of MTGase-catalyzed crosslinking in the noodle dough formulation could significantly improve maintenance of these micronutrients and health benefits.

Cabrera-Chávez et al. (2008) showed that the whole/partial replacement of wheat flour with the mixture of MTGase and flour of legumes and pseudo-cereals can highly decrease the prevalence rate of celiac disease. In addition to the generation of cross-links between protein molecules, catalysis of the deamidation reaction is done by MTGase at its high concentrations, at pH 6.5 and even where there is no accessible primary amine as co-substrate (Skovbjerg et al. 2004). Since there is a unit-specific substrate (gliadin) for MTGase and tissue transglutaminase (TG2), MTGase-supplementing the foods having gliadin might thus increase immunotoxicity of deamidated gliadin. Ruh et al. (2014) evaluated the immunological reactivity of gliadin-extracts obtained from control and MTGase-treated pasta doughs using the immunoblotting and ELISA techniques. No significant difference in immunoreactivity of IgA- and IgG-type antibodies present in celiac disease patients' sera was detected against gliadin extracts obtained from both pastas untreated and treated with MTGase. Similar antigenicity results were found by Takács et al. (2008) for wheat-based pasta products with a low cholesterol level.

Conclusion and future remarks

The present review represents a comprehensive collection of MTGase impacts on the critical quality characteristics of noodles and pasta products. This enzyme by forming heat-resistant covalent cross-links provides the suitable textural qualities for these unique products with a more breaking energy. Encapsulating the starch granules into the strong protein matrix introduced by MTGase can reinforce the dough structure, causing an inconsiderable sticky surface of final products. Increasing the cross-links number at high MTGase concentrations can significantly decrease the cooking loss rate by potentiating a physical/structural barrier against water penetration. MTGase addition to the dough formulation of noodle/pasta can clearly support a high-quality product with improved sensory and color attributes. A slow digestion rate for MTGase-supplemented products is expected because the entrapment of starch granules into closed matrix of the enzyme decelerates the movement of starch substrates and activity of hydrolyzing enzymes. Since a high capacity in consuming these healthy functional products has been recently recorded, bio-production of MTGase in large-scale industrial fermenters using superior microbial strains is of great importance. A research lack on the application of natural antioxidant compounds to enrich pasta products using MTGase is also felt. It seems that the preparation of micro/nanocapsules containing nutritive ingredients using novel encapsulation techniques and their incorporation into the dough formulation can be an efficient solution to highly improve the quality of final product, and absorption/bio-availability of the target bioactive components.

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