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Review of the effects of different processing technologies on cooked and convenience rice quality

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Abstract

Background

Commercially available **convenience rice** such as retorted, quick cooking or frozen rice suffers from sensory deficiencies compared to home cooked rice. The mechanisms causing deterioration in texture and flavour during convenience **rice processing** are, in many cases, poorly understood.

Scope and Approach

This review describes pre-cooking methods including washing and soaking, cooking methods including cooking in excess water, by absorption and by high pressure, and post-cooking technologies including cooling, freezing, retorting, canning, drying and storage, as well as the influence of each process on **physical properties** and sensory attributes of cooked rice.

Key findings and conclusions

Water diffusion and starch leaching, which occur in many processing steps, are important factors affecting **cooked rice quality**. Soaking saves energy by reducing cooking time. Cooking by absorption increases stickiness, but does not ensure uniform moisture distribution compared to cooking in excess water, thus is not applicable for rice manufacturers. Leached amylose during soaking and cooking affects hardness and stickiness of cooked rice significantly. Non-thermal treatments such as high pressure soaking and cooking has potential to improve **rice sensory**

properties compared to high temperature treatments, which change colour and flavour of convenience rice. Drying and freezing results in a porous structure resulting in spongy texture after rehydration and thawing, respectively. During storage, starch retrogradation deteriorates texture, but can be retarded by high pressure processing or storage below the glass transition temperature. Much is known about processing factors that affect freshly cooked rice, but more substantial knowledge of how processing steps affect the structure property relationships and sensory properties of convenience rice will assist manufacturers to specifically design products to meet the ever growing consumer demands for convenience food.

Keywords: Convenience rice; rice cooking; rice processing; cooked rice quality; rice sensory properties; rice physical properties

1 Introduction

Rice is cooked in a variety of ways in the home with the method used usually relating to the cultural background of the consumer. Some cultures soak rice before cooking while others cook rice directly by boiling it in excess water or by cooking it with an absorption method (Crowhurst & Creed, 2001; Son, Do, Kim, Cho, Suwonsichon, & Valentin, 2013; Tian, Zhao, Xie, Wang, Xu, & Jin, 2014; Tsugita, Ohta & Kato, 1983). Other methods involve steaming (Metcalf & Lund, 1985) or cooking in a pressure cooker (Leelayuthsoontorn & Thipayarat, 2006; Son *et al.*, 2013). Rice can also be cooked in a microwave or under very high pressure (Boluda-Aguilar, Taboada-Rodríguez, López-Gómez, Marín-Iniesta, & Barbosa-Cánovas, 2013).

Rice is a staple food in many countries and relatively easy to cook because it simply requires water and heat, especially with an automatic rice cooker, but the standard home cooking processes usually take in excess of 15 min. Manufacturers provide consumers with a pre-processed alternative for convenience, and which is favourable for those occasions where only single portions are required (Gofton & Ness, 1991). Convenience food saves the consumer time and energy use in acquisition, consumption and disposal in the process of food consumption (Brown & McEnally, 1992). Convenient rice dishes that include meat and vegetables provide a very attractive option as a 'ready meal', and the market for these is expanding rapidly, underpinned by microwave cooking and new packaging technologies. The Asian market for convenience rice was established 20 years ago and has grown exponentially (Byun, Hong, Mangalassary, Bae, Cooksey, Park, & Whiteside, 2010). Globally, the convenience meals market is expected to grow by 3.2 % from $ 1.1 trillion in 2011 to $ 1.3 trillion in 2016 and much of this growth is predicted to occur in China (Schmidt Rivera, Espinoza Orias & Azapagic, 2014).

Several studies have been performed on determining the effect of process variables on the sensory quality and morphology of the cooked rice. This includes studies that showed how the shape and volume of rice was affected by the presence and absence of a soaking stage prior to cooking, and variations in cooking time (Bhattacharya, 2011; Mohapatra & Bal, 2006; Sabularse, Liuzzo, Rao, & Grodner, 1991) as well as those that focused on how sensory quality is affected by temperature, cooking time and water-to-rice ratio (W/R) (Bett-Garber, Champagne, Ingram, & McClung, 2007; Leelayuthsoontorn & Thipayarat, 2006; Srisawas & Jindal, 2007). In comparison, relatively little is published on the effect of process variables on the sensory quality of convenience rice. Recent advances have focused on extending the shelf life of convenience rice via additional post-cooking processing steps such as high temperature, high pressure, freezing or drying that seek to destroy bacteria and their spores and/or prevent spore germination and bacterial growth. These additional processes alter both the flavour and overall quality aspects of the convenience rice and result in a product considered to be inferior to freshly cooked rice (Kwak, Kim, Kim, Ahn, Jung, Jeong, & Kim, 2013). If the cooked rice is eaten without any sauce or seasoning the unacceptable change in aroma is perceived more strongly (Tsugita, 1985). As consumers judge food quality mainly in terms of its sensory and nutritional characteristics (Steptoe, Pollard & Wardle, 1995), the food industry faces the challenge of developing new technologies to produce shelf-stable convenience rice that tastes homemade despite the many processing steps. To unlock potentially large international market for convenience rice produce and meals, it is imperative to understand how cooked rice quality is influenced by each processing step before, during and after cooking, and how the mechanical, structural and sensory properties are affected. This knowledge will assist food manufacturers to design high quality, shelf-stable, convenience rice. Therefore, the most commonly used pre-cooking, cooking and post-cooking processing technologies applied to freshly cooked and convenience rice and their effect on eating quality will be discussed in this review.

2 Processing technology and influences on cooked and convenience rice quality

This section reviews processing technologies for home cooking and large scale production of cooked rice that includes pre-cooking, cooking and post-cooking stages, and reviews how these influence the rice physical properties and sensory attributes. Pre-cooking stage includes washing and soaking of rice; various cooking methods include cooking in excess water, using limited water absorption and by utilising high pressure; and post-cooking stage includes treatments such as retorting, canning, cooling, freezing, drying and storage of cooked rice. A block flow diagram highlighting each stage and various methods utilised is given in Fig. 1, whereby different combinations are possible to produce freshly cooked and convenience rice with certain properties. Table 1 provides a summary of the main processes used within each stage and highlights their most important impact on cooked rice quality.

2.1 Pre-cooking

2.1.1 Washing

Washing raw rice with water before cooking is common to remove milling dust and any remaining hull or bran with washing repetitions varying from 2 to 5, depending on the rice variety and the cooking method used (Champagne, Bett-Garber, Fitzgerald, Grimm, Lea, Ohtsubo, Jongdee, Xie, Bassinello, Resurreccion, Ahmad, Habibi, & Reinke, 2010). Rice varieties such as Basmati with a high amylose content from Pakistan, India or Iran are washed 3 to 5 times before they are cooked in excess water, whereas rice with a medium amylose content from Thailand, China, Pilippines, Japan or Australia are washed 2 to 3 times and cooked in a rice cooker with the absorption method (Champagne *et al.*, 2010). This study however does not state why these number of repetitions were chosen. Rice washed three times has been shown to cause less deterioration in flavour and colour after the cooked rice was stored for up to 24 h than rice washed only once (Fukai & Tukada, 2006). This is because around 60 – 80 % of total surface lipids were removed by one washing step for 5 or 10 min, with a reduction of free fatty acid and conjugated dienes relative to unwashed control samples (Monsoor & Proctor, 2002). The decomposition of rice surface lipids on the surface of rice which are mainly composed of glycerides from residual rice bran that hydrolyse to free fatty acids through lipase and subsequent oxidation, produce a rancid and stale flavour (Takano, Kamoi & Obara, 1989). Therefore washing may be a practical means to reduce free fatty acids and off-flavour development in cooked milled rice from lipid oxidation (Monsoor & Proctor, 2002). The washing procedure will also remove free starch produced by the milling process which may alter rice texture by changing grain-grain and grain-surface adhesion in a similar way to starch/amylose leaching, though this hypothesis requires greater investigation.

2.1.2 Soaking before cooking

Soaking rice in excess water before cooking is a traditional practice in Japan, Korea, and other Asian countries, and is a factor affecting cooking quality, with the soaking typically done below gelatinisation temperature of rice starch, at different pressure levels, and with soaking times varying between 15 and 120 min (Champagne, 2008; Champagne *et al.*, 2010; Horigane, Takahashi, Maruyama, Ohtsubo, & Yoshida, 2006; Tian *et al.*, 2014; Yamakura, Okadome, Suzuki, Tran, Homma, Sasagawa, Yamazaki, & Ohtsubo, 2005b). Soaking rice under various conditions is also a common pre-treatment for several convenience rice products such as frozen rice or quick cooking rice, as it distributes water evenly within the grain, leading to a reduction in cooking time and energy consumption (Chakkaravarthi, Lakshmi, Subramanian, & Hegde, 2008; Das, Subramanian, Chakkaravarthi, Singh, Ali, & Bordoloi, 2006).

Water diffuses into rice grains due to the moisture gradient between the surface and the centre of the grain, and diffuses more rapidly into milled grains through cracks and chalky areas before diffusing to the outer layer (Horigane *et al.*, 2006). The moisture content reaches a plateau after 30 – 60 min (Boluda-Aguilar *et al.*, 2013; Das *et al.*, 2006) and a positive correlation between temperature and the rate of water diffusivity has been shown (Bello, Tolaba & Suarez, 2004; Chakkaravarthi *et al.*, 2008; Muramatsu, Tagawa, Sakaguchi, & Kasai, 2006; Suzuki, Kubota, Omichi, & Hosaka, 1976). Starch granules swell and expand during soaking, which has been found to cause more complete starch gelatinisation after cooking compared to unsoaked rice. The initial moisture content of the raw rice influences the hydration homogeneity, degree of gelatinisation, percentage of broken kernels and degree of starch leaching (Genkawa, Tanaka, Hamanaka, & Uchino, 2011; Han & Lim, 2009; Prasert & Suwannaporn, 2009; Seki & Kainuma, 1982).

A soaking temperature of 15 °C, compared to 35 °C, leads to more cracks in the outer layer of the rice grain (Genkawa *et al.*, 2011) and consequently, the grain is expected to break more easily during cooking. Lower soaking temperature decreases the rate of water diffusion, producing a difference in the specific volume of the outer layer and the centre of the grain resulting in a tensile stress that is likely to form cracks if above the tensile strength of the grain (Genkawa *et al.*, 2011). Medium amylose rice (16.77 – 16.95 %) is more susceptible to crack formation during soaking than high amylose rice (27.64 %) (Kasai, Lewis, Ayabe, Hatae, & Fyfe, 2007).

A comparison of cooking kinetics showed that soaked rice cooks faster (~9 min) than unsoaked rice (~15 min) (Chakkaravarthi *et al.*, 2008). As cooking proceeds, the cooking rate is first limited by the physical change of rice components including swelling and gelatinisation of starch granules, due to the interaction of heat and water at the surface of the grain. After this, water diffuses through the outer layer of gelatinised starch to the non-hydrated core, allowing starch to gelatinise, becoming the limiting factor for gelatinisation. In contrast, rice that is fully hydrated after 30 min of soaking does not display a decrease in cooking rate due to water diffusion as water required for gelatinisation is already available (Chakkaravarthi *et al.*, 2008). If water diffusion into the grains is insufficient, the starch located in the central part of the grain may not become fully gelatinised during cooking, resulting in a hard texture (Seki & Kainuma, 1982).

During soaking, components such as sugars, soluble proteins and non-starch bound lipids leach from grains (Chiang & Yeh, 2002; Patindol, Gu & Wang, 2010).The rate and extent of leaching increases with increased soaking temperature and time (Bello *et al.*, 2004; Chiang & Yeh, 2002; Han & Lim, 2009). Damage to the structure of the rice grain, such as chalky areas or cracks formed via milling may also encourage molecules to leach from the rice (Bhattacharya, 2011). The leaching of reducing sugars and free α-amino nitrogen, responsible for Maillard reactions causing changes in colour, was increased by soaking time and temperature; thus the more leached out, the less colour deterioration upon subsequent cooking occured, with the effect more prominent in brown rice than milled rice (Lamberts, Brijs, Mohamed, Verhelst, & Delcour, 2006).

A higher soaking temperature causes a higher moisture content after soaking, which resulted in increased adhesiveness and decreased hardness (Han & Lim, 2009). Starch leached from cooked rice consists mostly of amylose due to its smaller molecular size and greater mobility (Han & Lim, 2009) and was shown to correlate positively to instrumental hardness of cooked rice (Ong & Blanshard, 1995). However, when the total amount of leached components was quantified, no significant correlation with instrumentally measured hardness and adhesiveness was shown (Ong & Blanshard, 1995; Patindol *et al.*, 2010). In terms of flavour, soaking of 11 rice varieties for 30 min was shown to influence cooked rice flavour and sweet taste negatively, suggesting leaching of small flavour-active metabolites that are discarded with the soaking water, but the change in flavour was not related to textural changes (Calingacion, Boualaphanh, Daygon, Anacleto, Sackville Hamilton, Biais, Deborde, Maucourt, Moing, Mumm, de Vos, Erban, Kopka, Hansen, Laursen, Schjoerring, Hall, & Fitzgerald, 2012; Champagne, 2008).

The rate of water diffusion is elevated under pressure or vacuum and therefore shortens the soaking time for rice (Bello Marcelo, Tolaba Marcela & Suárez, 2008; Tian *et al.*, 2014). Soaking rice under a vacuum for 30 min resulted in a 1 – 2 % higher moisture content than under atmospheric pressure, indicating that the vacuum soaking might cause wider channels between starch granules and benefit water entry due to a pressure difference between the inside and outside of the grain (Tian *et al.*, 2014). It is also possible that the wider channels are created between cell walls facilitating water diffusion. After cooking, vacuum soaked rice did not show a significant difference in instrumentally measured hardness, springiness or cohesiveness compared to rice soaked at atmospheric pressure (Tian *et al.*, 2014).

Compared to vacuum or atmospheric pressure, soaking under high pressure (HP) at 300 or 400 MPa at 20 °C resulted in a significant increase in moisture in the grain (Huang, Jao & Hsu, 2009; Tian *et al.*, 2014). At soaking pressures above 600 MPa starch gelatinises at ambient temperature (Hu, Xu, Jin, Tian, Bai, & Xie, 2011), but at 300 MPa and 20 °C, rice showed only 10 % gelatinisation (Huang *et al.*, 2009). The cooked, HP soaked rice at 300 and 400 MPa decreased in instrumental hardness and increased in instrumental springiness and cohesiveness, measured with a texture analyser, compared to rice soaked under ambient pressure (Tian *et al.*, 2014). The decrease in hardness of HP soaked rice is explained by the decreased leaching of amylose and amylopectin. Amylose content is one parameter amongst others positively correlated to cooked rice hardness (Sowbhagya, Ramesh & Bhattacharya, 1987), thus with a higher amylose retention in the grain, an increase in hardness would be expected. A redistribution of amylose and amylopectin under HP has been suggested (Tian *et al.*, 2014), but the explanation for the mechanism causing the change in textural properties of HP soaked rice was not supported by experimental evidence. The description that the macrostructure of HP treated rice grains which was broken into some large pieces increases springiness, and that the increase in cohesiveness was due to redistribution of amylose and amylopectin needs additional investigation.

Soaking rice at 55 °C, compared to 25 °C, with subsequent HP treatment resulted in an increase in glucose content of rice compared to non-soaked rice, likely due to enhanced enzyme activity and mobility at 55 °C (Yamakura, Haraguchi, Okadome, Suzuki, Tran, Horigane, Yoshida, Homma, Sasagawa, Yamazaki, & Ohtsubo, 2005a). Unfortunately no sensory profiling was reported, though a sweeter taste could be expected because small sugar molecules may be pressed into the rice grain when the soaking water is not discarded. Moreover, soaking under HP improved the lightness and intensity of the colour of cooked rice compared to soaking under atmospheric pressure, due to the inhibition of enzymatic browning from restriction of oxygen, leading to a lower enzyme activity (Tian *et al.*, 2014).

In conclusion, soaking is worth considering as a processing step for rice manufacturers to shorten the cooking time and save energy. If less sticky rice is desired, it is recommended to wash and soak rice for up to 30 min before cooking to remove excess starch and free fatty acids on the grain surface, which additionally assists to decrease flavour deterioration. Soaking times can be reduced via either a higher temperature, HP or a vacuum process. More knowledge about the structure-property relationship is necessary to describe the effect of HP soaking on the redistribution of starch and water in rice grains altering cooked rice texture to inform industry about the potential of HP to design convenience rice with desired textural properties.

2.2 Cooking

Depending on the cultural background, cuisine and rice variety (Son *et al.*, 2013), cooking rice at home is mainly achieved by one of two major methods: cooking by absorption with a predetermined amount of water, and cooking in excess water at temperatures above the gelatinisation temperature of the variety. The food industry typically cooks rice using the excess water method as it can be conducted as a continuous process and allows an even distribution of moisture within rice grains. The cooking process comprises two mechanism: one is the gradual absorption of water from the surface to the core of the grain, and the other is the structural changes of the rice components by heating with water (Suzuki *et al.*, 1976). High pressure processing (HPP) is a non-thermal process to gelatinise rice starch and became a popular technology in food processing since 2000 (Norton & Sun, 2008) due to the lack of heat and the attendant chemical changes within food that comes with high temperature processing.

2.2.1 Cooking in excess water

One cooking method used is to add rice to boiling, excess water for a specific time (Mestres, Ribeyre, Pons, Fallet, & Matencio, 2011; Meullenet, Gross, Marks, & Daniels, 1998). This method is used at home and on industrial scale. In a standard laboratory scale procedure, the water-to-rice ratio (W/R) ranges between 10:1 and 20:1 (Chakkaravarthi *et al.*, 2008). In order to determine the end point of cooking in laboratories, rice grains are periodically sampled during cooking and pressed between two parallel glass plates. When grains do not show a starchy core in the centre anymore the sample is considered to be completely cooked (Billiris, Siebenmorgen, Meullenet, & Mauromoustakos, 2012a; Mohapatra & Bal, 2006). Though the rice is cooked through completely, this stage of cooking does not necessarily represent the most desirable texture. Cooking in excess water does not limit the diffusion of water, thus the rice cooks until it completely disintegrates. After the rice is cooked, the excess water is discarded with all the leached components.

The cooking rate is the amount of cooked rice as a function of cooking time, and is strongly affected by the temperature and the amount of cooking water (Bello, Tolaba & Suarez, 2007; Suzuki *et al.*, 1976). When water temperature is increased to the gelatinisation temperature, starch granules swell irreversibly, lose their crystallinity and gelatinise (Metcalf & Lund, 1985). Rice starch starts to gelatinise between 61 and 85 °C depending on the variety (Cuevas, Daygon, Corpuz, Nora, Reinke, Waters, & Fitzgerald, 2010) at atmospheric pressure. When a long grain variety was soaked/cooked from 25 – 90 °C, the water absorption curves showed a rapid increase in the diffusion of water at around 65 °C (Bello *et al.*, 2007). The changes in the activation energy for diffusion and physical change at 60 °C indicate that below this temperature the structural change of water and rice components was the limiting factor while above 60 °C the diffusion of water became the limiting factor for water absorption with the gelatinised starch physically preventing penetration of water (Bello *et al.*, 2007; Suzuki *et al.*, 1976). These results are consistent with the study of Chakkaravarthi et al. (2008).

The amount of starch that leaches from milled rice during soaking at 85 ºC ranges from 1.9 – 3.7 % (Wada, Umemoto, Aoki, Tsubone, Ogata, & Kondo, 2010) and was positively correlated with the overall eating quality, including glossiness, taste, hardness and stickiness, whereas the amount of leached amylose correlated negatively with overall eating quality, as measured by sensory analysis with a Japanese panel (Wada *et al.*, 2010). Japanese consumers prefer stickier rice, and a higher amount of amylose in the leachate has been reported to decrease stickiness (Hanashiro, Ohta, Takeda, Mizukami, & Takeda, 2004), as the leached starch and amylose is discarded with the cooking water. As well as affecting the amount of leached components, the moisture content strongly affects cooked rice texture. In excess water, diffusion is not limited, thus the moisture content increases with increasing cooking time and rice cooked in excess water for 16 min was significantly harder than cooked for 18, 20 or 22 min as measured with a texture analyser (Billiris *et al.*, 2012a).

2.2.1 Cooking by absorption

Another popular home cooking method, used by essentially all electronic rice cookers, is to cook rice with a predetermined amount of water until the water is fully absorbed. A recommendation for the optimum W/R was given by the International Rice Research Institute in the Philippines depending on the amylose content of rice: for each unit of milled rice, 1.3 times as much water for waxy rice, 1.7 times as much water for low amylose (12 – 20 %) rice, 1.9 times as much water for intermediate amylose (21 – 25 %) rice, and 2.1 times as much water for high amylose (> 25 %) rice is added to ensure well cooked rice (Perez & Juliano, 1979).

In contrast to cooking in excess water, cooking by absorption does not ensure a uniform treatment throughout the bulk sample because the moisture content of individual rice kernels varies with their location due to non-uniformity of heat distribution (Das *et al.*, 2006). Sensory properties of rice cooked with the absorption cooking method have been analysed, however little research has been done on the water diffusion and cooking mechanism of this method. Kasai et al. (2005) cooked rice grains with a fixed water amount and showed that the distribution of moisture inside the grains changed during boiling. Water diffuses through the outer layer of rice grains first until completely absorbed. As boiling continues, absorbed water interacts with ungelatinised starch until water distribution is even in the whole rice grain (Kasai, Lewis, Marica, Ayabe, Hatae, & Fyfe, 2005), preconditioned that there was sufficient water for complete gelatinisation. Unfortunately, the leaching of components was not measured, though leached starch gelatinised on the surface of the grains might decrease the diffusion of water physically as cooking proceeds. A low W/R ratio might therefore create a gelatinised starchy coating on the surface the grain, without leaving enough water to gelatinise the starch at the centre of the grain, leading to a hard core. Comparing rice with the same moisture content that has been cooked in excess water or with the absorption method might therefore show a different distribution of moisture within the grain, but this hypothesis remains to be investigated. This effect may be prevented by soaking the rice prior to cooking as described earlier.

A rice cooker was used by Bett-Garber et al. (2007) with low, recommended and high W/R to test the effect of W/R on sensory attributes of various cooked rice. Sensory analysis showed that a higher W/R increased the initial starchy coating, slickness, stickiness between grains, cohesiveness, and uniformity of bite, while decreasing the hardness, stickiness to lips, springiness and chewiness (Bett-Garber *et al.*, 2007). Starch that leaches from rice grains can form a gel that coats the surface of the rice kernel (Fitzgerald, 2004) and higher W/R results in a greater amount of starch leaching, thus the coating of grains increases stickiness. this is in contrast to cooking in excess water, where the leached components are discarded with the cooking water (Wada *et al.*, 2010). The sensory attributes of roughness, cohesiveness of mass, moisture absorption, residuals or toothpacking were not significantly affected by W/R (Bett-Garber *et al.*, 2007) nor were any flavour attributes (Bett-Garber *et al.*, 2007; Srisawas & Jindal, 2007).

Consumer preference for cooking method is dependent on the rice variety being consumed. For example, the acceptance of long grain and Thai Jasmine rice was higher when cooked by absorption, producing stickier, firmer, drier rice with a more acceptable flavour and appearance while Basmati rice was preferred when cooked in excess water (Crowhurst & Creed, 2001).

For the purposes of industrial production of convenience rice, the absorption method has serious limitations due to being a batch process with non-uniform distribution of heat and moisture during cooking, though this method is 33 % more energy efficient compared to the excess water method (Billiris, Siebenmorgen & Wang, 2012b; Das *et al.*, 2006), and is recommended when a stickier rice texture is desirable. However, design of a continuous process that utilises absorption method has the potential to produce a consistent product, in an energy efficient manner with reduced waste water production.

2.2.2 Cooking under pressure

One of the major issues faced by companies processing convenience rice is that both the flavour and texture of convenience rice are considered to be inferior to freshly cooked rice (Sabularse *et al.*, 1991). In Japan, HP treated, shelf-stable packets of rice have been successfully launched.

When the temperature of the cooking water exceeds 100 ºC, using a combination of high temperature (140 ºC) and pressure up to 0.5 MPa, rice grains are shorter, softer and stickier in texture with more off-white colour than when they are cooked in ambient condition (Leelayuthsoontorn & Thipayarat, 2006). The microstructural analysis revealed that the softer texture at higher cooking temperature may be related to the increase in pore size and thickness of the sponge-like texture of the inner layer of the endosperm (Leelayuthsoontorn & Thipayarat, 2006). Excess water at temperatures below 140 ºC was reported not sufficient to generate a coating film of leached amylose on rice grains that could increase stickiness (Leelayuthsoontorn & Thipayarat, 2006). However this contradicts other studies, where the leaching of amylose is reported to be negatively correlated with stickiness at cooking temperatures below 140 ºC (Hanashiro *et al.*, 2004; Mestres *et al.*, 2011). In the study of Mestres et al. (2011), the rice was not rinsed after cooking, whereas the rice used by Leelayuthsoontorn et al. (2006) was rinsed and cooled after cooking, so the starchy coating is expected to be rinsed off and may reduce stickiness of the grains. The cooking temperature altered the external appearance of cooked rice and its texture, while an increase of pressure up to 0.5 MPa seemed to have little or no effect (Leelayuthsoontorn & Thipayarat, 2006).

When pressure in the range of 100 – 1000 MPa is combined with moderate temperature, 25 – 50 ºC, and a short processing time from 2 – 20 min, it is referred to as high pressure processing (HPP) (Knorr, Heinz & Buckow, 2006). The mechanism of HP gelatinisation of starch is different from heat induced gelatinisation. Under heat treatment and in excess water, the amorphous region of starch granules swells before helix-coil transitions in amylose and amylopectin, removing crystalline order, with eventual loss of granular structure (Buckow, Heinz & Knorr, 2007). In contrast, scanning electron microscopy images show that non-waxy starch granules retain their integrity after HPP at 600 MPa, while waxy starch granules lose their integrity (Hu *et al.*, 2011). This indicates that amylose, perhaps due to its long chain structure, stabilizes the granules and prevents them from disintegrating, whereas granules composed entirely from amylopectin are more readily degraded by pressure. Under pressure, dissociation and helix unwinding might be suppressed because van der Waals forces and hydrogen bonds are stabilized and strengthen the helix structure (Buckow *et al.*, 2007), thus decreasing the leaching of amylose; consequently, starch granules keep their integrity under pressure. HP treatment is also suggested to redistribute the water in the amorphous region leading to a shift in the glass transition temperature, thus gelatinisation is possible at room temperatures due to lowered energy requirement for melting the crystalline regions (Liu, Selomulyo & Zhou, 2008). The gelatinisation under HP is dependent on pressure, starch concentration, time, temperature and solvent quality (Liu, Hu & Shen, 2010). As an example, rice starch granules in a suspension (20 % w/w) started to lose their integrity at 600 MPa at room temperature after 30 min (Li, Bai, Mousaa, Zhang, & Shen, 2012).

A rice flour slurry pressurised at 650 MPa for 15 min was compared to a heat treated counterpart (90 ºC for 30 min) and showed significantly higher elastic modulus as measured with a rheometer (Ahmed, Ramaswamy, Ayad, Alli, & Alvarez, 2007). The elastic modulus increased with increased pressure treatment (350 – 650 MPa at ambient temperature, 15 min). In this case, rice flour slurry containing protein required higher pressure to gelatinise completely compared to rice starch slurry without protein. The reason might be that protein and starch compete for water (Ahmed *et al.*, 2007); the more water is bound to protein, the less is available for starch, thus a higher pressure is needed for complete gelatinisation. There is a wealth of knowledge about HPP and its impact on gelatinisation and leaching behaviour of various starch and starch gels, however knowledge about the effect on whole rice grains is needed.

Soaked and subsequently high pressure treated rice grains at 300 or 400 MPa for 2 or 4 min showed increased instrumental hardness and cohesiveness than rice that was freshly cooked in the microwave. After microwaving the HP treated rice for 90 s hardness and cohesiveness decreased and were similar to the sample that was only microwaved (Boluda-Aguilar *et al.*, 2013). The results of changes in textural properties are consistent with those reported elsewhere (Tian *et al.*, 2014). The higher hardness of HP treated rice before microwaving may be due to the incomplete gelatinisation and a low moisture content of 32 – 35 %, respectively (Boluda-Aguilar *et al.*, 2013). The moisture contents of microwaved rice with and without HP treatment were not compared, therefore it remains to be investigated why the hardness and cohesiveness changed after microwaving of HP treated rice. Compared to a Jasmine rice cooked with a W/R of 1.5 in a rice cooker, the HP treated, microwaved rice was significantly harder (Srisawas & Jindal, 2007). A satisfactory explanation and discussion about the mechanism at a molecular level that might cause these textural differences is needed.

The effect of HPP on the aromatic profile of rice is complicated and dependent on the rice varieties as well as the pressure-temperature combination used (Deng, Zhong, Yu, Yue, Liu, Zheng, & Zhao, 2013). Volatile compounds from a Jasmine and japonica rice variety, soaked at 25 °C, were analysed after HPP at 200, 400 and 600 MPa before undergoing solid phase micro extraction gas chromatography mass spectrometry (Deng *et al.*, 2013). Changes in the volatile composition were observed, with aldehyde concentration decreasing more in the Jasmin than the japonica rice. Pressure treatment at 200 or 400 MPa increased the concentration of alcohols, ketones, esters and olefins, but reduced those of heterocycles, alkanes and arenes. Heterocycles such as 2-acetyl-1-pyrroline, which is considered to be the major contributor to aroma in aromatic rice (Buttery, Ling & Juliano, 1982), changed in a inconsistent pattern depending on pressure and rice variety (Deng *et al.*, 2013). Since only two rice varieties were investigated and these two rice samples show inconsistent volatile change after HPP, there is the opportunity to test the effect of HPP on volatile compounds on a larger set of samples of different rice varieties, including brown rice. The flavour change in convenience rice was tested with Jasmine rice soaked for 0 – 60 min followed by processing it at 300 and 400 MPa for 2 and 4 min respectively (Boluda-Aguilar *et al.*, 2013). Following this, a second treatment of 570 MPa was applied for 20 min, the rice was cooled and reheated in a microwave for 90 s and compared to an untreated control rice that was freshly cooked in a microwave for 10 min. Sensory analysis showed a higher acceptance for rice undergoing a single cycle of HP treatment compared to freshly cooked rice with the highest sensorial appreciation obtained using a soaking period of 45 – 60 min, followed by a pressure treatment at 300 MPa (Boluda-Aguilar *et al.*, 2013). The pressure treatments greater than 300 MPa led to significant losses in perception of aroma when compared to the freshly cooked sample, which is due to alterations in the composition of volatile compounds (Deng *et al.*, 2013). Since interactions between individual flavour compounds and small changes in the concentration of one compound may have major effects on the overall flavour, it is necessary to conduct descriptive sensory analysis in addition to pure chemical and instrumental analysis to better understand the effects of HPP on the overall flavour perception.

In summary, producing consumer acceptable convenience rice requires accurate control over the cooking methodologies that may vary with rice type. The different cooking processes including boiling in excess water, absorption of a predetermined water amount and pressure cooking modify the texture and flavour of rice grains, often in a predictable manner. The necessity of using a batch-cooking process when using absorption or pressure cooking methods causes difficulties in applying these techniques to industry on a big scale, thus, excess water is the most common cooking method used. With this cooking method, water absorption is not limited, causing greater solid leaching, mainly starch, and by removing the starchy coating, reducing the stickiness of rice. HPP as a non-thermal process is a promising technique to produce convenience rice. The research conducted on HPP indicates that pressures affects the amorphous and ordered structure of starch, decreasing amylose leaching and resulting in harder and less stickier rice. Therefore, it would be interesting to investigate how the ordering and interaction between starch molecules change under HP and how cooked rice texture can be modified accordingly. The interaction between pressure and rice protein in rice flour slurry affects texture and remains to be investigated whether it has an effect in whole rice grains. HP cooking alters the volatile compounds at certain pressure, which impacts the flavour and acceptability of convenience rice, however, a more systematic analysis of alterations in the volatile composition of different rice varieties and its effect on sensory is necessary.

2.3 Post-cooking processes

Post-cooking processes are typically conducted in the industry to supress microbiological growth and extend the shelf life of rice, and are divided into three categories: (1) low temperature treatments such as cooling or freezing; (2) high temperature treatments such as retorting and canning, drying; and (3) storage conditions, during which textural properties of cooked rice change due to structural changes in starch, the movement of water into or out of grains, and the loss and change of flavour components. Applying one or a combination of post-cooking processes can be very effective to prevent or delay changes to sensory properties.

2.3.1 Low temperature treatments

Cooling or refrigerating is rarely used with rice in home cooking before consumption, but it is important for convenience rice to be cooled quickly after cooking, and before sterilisation (e.g. in retorted rice) to prevent further gelatinisation of starch and the growth of surviving food pathogens (Zhang & Sun, 2006). The most commonly applied methods to cool cooked rice are air-blast cooling and cold room cooling, both of which display different effects on the physical properties of rice (Ma & Sun, 2009). There was no change in instrumental hardness when using air-blast cooling, however the hardness and cohesiveness increased after cold room cooling for long grain rice, but not for Japanese or Jasmine rice (Ma & Sun, 2009). Cohesiveness only increased for long grain rice after air-blast cooling, and for long grain and Japanese rice after cold room cooling. There was little loss of moisture of long grain, Japanese and Jasmine rice when using air-blast cooling or in Japanese rice when using cold room cooling (around 1%), therefore, the cooling method and rice variety both affect textural change, whereas moisture loss had little or no impact (Ma & Sun, 2009). A higher cooling rate by cold room cooling (3.36 ºC/min) decreased instrumental hardness and increased adhesiveness of cooked rice compared to a slow cooling rate (0.4 ºC/min) (Yu, Ma, Liu, Menager, & Sun, 2010a). In contrast to Ma et al. (2009), there was no difference in moisture content after cooling, thus textural differences were correlated with reduced starch retrogradation enthalpy at a higher cooling rate.

Less common methods such as plate cooling, vacuum cooling or rinsing with cold water are also applied (Meullenet *et al.*, 1998; Smith, Rao, Liuzzo, & Champagne, 1985; Zhang & Sun, 2006). Vacuum cooling is the fastest cooling method and results in the greatest moisture loss (Zhang & Sun, 2006), and is, thus, expected to increase rice hardness. Rinsing rice with cold water is used to stop the cooking process prior to retorting (Smith *et al.*, 1985), and washes away the starchy coat of rice grains, which reduces the stickiness of rice (Wada *et al.*, 2010).

Freezing is applied to extend the shelf life of convenience rice, and frozen rice needs less time to prepare than raw rice. In Japan, frozen rice is a very popular, but expensive convenience rice product, due to its time and energy intensive production; it is either warmed in a microwave for 3.5 – 4.5 min or boiled for 2 – 3 min to prepare it for consumption (Ohtsubo, Okunishi & Suzuki, 2004). One way of commercially producing frozen rice is to first soak the rice, then steam cook it before cooling it with an air-blast cooler, then it is packed in cartons or pouches and frozen in air-blast freezers (Tressler, 1968). Similar to cooling processes, slow freezing rates (0.09 ºC/min) result in a significantly lower moisture content of cooked rice compared to a rapid freezing rate (1.45 ºC/min) (Yu *et al.*, 2010a). Simultaneously, larger ice crystals are formed at slow freezing rates which cause more damage to cellular structures, allowing water to migrate rapidly to the outside of the product during thawing (syneresis). For frozen rice, the transportation from the factory to the retailer and the consumer before consumption will involve freeze-thawing if there is any kind of breakdown in the cold storage chain, and this leads to undesirable changes in the texture. Syneresis occur upon thawing and phase separation is enforced, larger ice crystals are formed again after freezing, increasing the pore size of rice starch gel and producing a porous and spongy texture after reheating (Arunyanart & Charoenrein, 2008). In contrast, other studies reported that reheated frozen rice is virtually indistinguishable from its unfrozen counterparts and storage at -18 °C up to one year appears to have no deleterious effects on quality (Luh, 1991a).

Freezing cooked rice is effective at extending shelf life, however it is energy intensive and affects cooked rice texture significantly when freeze-thawing occurs. While the changes in texture are understood to some extent there is little information about the appearance or the change in volatile compounds and flavour of rice after chilling and freezing. The high energy cost in production and the vulnerability to failures in the cold storage supply chain increase the cost for the consumer and the risk to quality deterioration.

2.3.2 High temperature treatments

To produce convenience rice products that are shelf-stable at room temperature, a commercial sterilisation process is necessary, the most common of which is heat treatment. For low acid foods like rice, the product must undergo a treatment in the range of 112 – 125 ºC for 8 – 10 min for microbial as well as spore inactivation (Prakash, Ravi, Sathish, Shyamala, Shwetha, & Rangarao, 2005).

Retorted rice was first developed in Japan in the early 1970s (Ohtsubo *et al.*, 2004) and is a process of sterilisation after cooking or partially cooking rice. Over 750 million pouches of retorted foods are consumed in Japan annually, whereby steamed waxy rice with red beans accounts for 89 % of all retorted rice in Japan (Luh, 1991a). The retort process consists of time-temperature conditions required to sterilise a product and ensure it is safe for consumption and shelf-stable for up to 12 months (Prakash *et al.*, 2005). It is an in-package process, where the pre-cooked rice is filled into heat resistant pouches or cups, sealed and sterilised batch-wise in a steam retort plant, whereby the temperature time combination ranges from 112 °C for 30 min to 125 °C for 8 min, then after retorting, the pouches are cooled with water (Prakash *et al.*, 2005). Oil can be added before retorting to facilitate free flow of cooked grains during the filling procedure, although it is also possible to omit the cooking step before retorting to remove difficulties with handling sticky cooked rice (Kobayashi, Sasaki, Matsuo, & Ohba, 1991). Before sealing the rice pouches or cups, the air in the headspace is partially replaced by nitrogen to avoid undesirable colour development and oxidation (Kobayashi *et al.*, 1991).

A problem with retorted rice is off-flavour, and an inferior texture has been found to occur that has been associated with excess heating (Ohtsubo *et al.*, 2004). Compared to freshly cooked rice, retorted rice which was partially cooked and then heated again at 118 °C for 8 min with 10 % added oil was slightly harder and stickier as measured by a texture analyser compared to freshly cooked rice (Prakash *et al.*, 2005). The retorted rice without oil was harder and stickier than the rice processed with oil though the significance of this difference was not reported. When partial cooking is eliminated, time and energy can be saved with sensory acceptance tests rating the product as highly as rice cooked in excess water (Kobayashi *et al.*, 1991). It has not been reported how the retort process or the added oil changes the volatile compounds and aroma of rice, and this is worth exploring to assist the design of desirable convenience rice eating quality by adjusting relevant process parameters.

Another high temperature product is canned rice, which is available with meat, in casseroles, as Spanish rice, plain cooked rice, fried rice, rice puddings or as soups with rice (Luh, 1991a). These products are important for people where cooking facilities are limited or unavailable (Patindol, Gonzalez, Wang, & McClung, 2007), or when food must stay stable for several years under natural conditions (Ohtsubo *et al.*, 2004). Ideally, canned rice grains should be white, the kernels should remain separate and non-cohesive, with resistance to longitudinal splitting and fraying of edges and ends, and yield minimal leached solids into the broth (Bergman, Bhattacharya & Ohtsubo, 2004; Luh, 1991a; Webb, 1979). One production method is to fill partially cooked rice, that has been rinsed and cooled, without additional water into cans (Luh, 1991a; Roberts, Houston & Kester, 1953). This process is similar to retorting thus similar properties are assumed. To minimize grain cohesion during retorting, cooking oil, oil emulsion or emulsifiers are added (Ferrel, Kester & Pence, 1960; Prakash *et al.*, 2005). A second method to produce canned rice is to add parboiled or raw rice and excess water to cans before retorting, produced this way the grains remain white and well separated, but become distorted and mushy in appearance (Alary, Laignelet & Feillet, 1977) since water diffusion is not limited, thus rice grains undergo disintegration more readily. To prevent this, cross linking agents for starch such as epichlorohydrin, sodium trimetaphosphate or phosphorous oxychloride may be used (Rutledge, Islam & James, 1974; Rutledge & Islam, 1973). In comparison to rice without starch modification, 70 % less starch leached out resulting in increased integrity of rice grains during retorting and less clumping of grains. The modified rice was more stable after storage at 25 °C for 6 months and was also preferred by sensory panellists in comparison to its unmodified counterpart (Rutledge & Islam, 1976).

Canned rice has not been commercially successful because the excessive starch leaching during canning led to a loss of structural integrity, discolouration, unpalatable odour and poor cooking quality compared to instant parboiled rice (Gerdes & Burns, 1982).

2.3.3 Drying

By reducing the water activity of cooked rice, it is possible to prevent microbial growth, this is done most simply by applying high temperature to dry the rice. Drying cooked rice at high temperatures produces a quick cooking convenience rice that undergoes rapid rehydration before consumption due to its porous structure (Carlson, Roberts & Farkas, 1976). The variety of quick cooking rices, also called instant rices, ranges from relatively undercooked rice that needs 10 – 15 min of cooking time to a version that only needs 5 min preparation time and still reaches satisfactory acceptability (Luh, 1991b; Smith *et al.*, 1985). Important quality parameters for quick cooking rice are white colour and a fast rehydration rate, but quick cooking rice is sensorially inferior to freshly cooked rice with grains tending to crumble after rehydration (Luangmalawat, Prachayawarakorn, Nathakaranakule, & Soponronnarit, 2008; Luh, 1991b; Prasert & Suwannaporn, 2009; Sripinyowanich & Noomhorm, 2013). Many patents on the production of quick cooking rice have been filed (Baz, Hsu & Scoville, 1992; Carlson, Roberts & Farkas, 1979; Lin & Jacops, 2002), but little is reported about sensory analysis of quick cooking rice compared to freshly cooked rice. The principle to produce quick cooking rice is to soak the rice until it reaches a certain moisture level (e.g. 30 %) then to cook or pre-gelatinise it and dry it afterwards to 5 – 10 % moisture; this prevents retrogradation and enables a shelf life of several years at room temperature (Ohtsubo *et al.*, 2004; Roberts, Carlson & Farkas, 1979; Semwal, Sharma & Arya, 1996). Driers for cooked rice include hot air drying (Luangmalawat *et al.*, 2008; Semwal *et al.*, 1996), flat bed drying (Prasert & Suwannaporn, 2009), convective air drying and freeze drying or some combination of methods (Smith *et al.*, 1985). During drying, water evaporates from the product, and the rate of evaporation is a function of the temperature, vapour pressure gradient, mass diffusion of water from the grain, and the distance for vapour movement within the grain structure (Singh & Heldman, 2001). Initially, the surface of cooked rice is almost saturated with water, and the water inside replaces the surface water, as it evaporates. As drying progresses, the surface dries and a porous structure forms (Luangmalawat *et al.*, 2008). The drying rate at a particular temperature decreases as water content decreases, this is due to a decrease in heat transfer due to the low thermal conductivity of gas compared to liquid in the highly porous structure (Singh & Heldman, 2001). When the moisture content of rice falls below 30 % (d.b.), the drying rates were insignificantly different between high (120 °C) and low temperature (50 °C) (Luangmalawat *et al.*, 2008). The high velocity air stream of a centrifugal fluidized bed dryer rapidly carries moisture away from the surface and prevents grains from sticking together, which is desired for cooked medium and short grain rice of high stickiness (Roberts *et al.*, 1979). Increased drying temperatures caused an increase in hardness and chewiness after rehydration of the instant rice (Prasert & Suwannaporn, 2009) and increased the yellow colour of cooked rice, especially when air is above 100 °C, likely due to Maillard reactions (Luangmalawat *et al.*, 2008). Despite the colour change, there was no significant difference in shrinkage or rehydration capability of rice when the drying temperature was varied from 50 – 120 °C (Luangmalawat *et al.*, 2008), which is in contrast to a previous study (Prasert & Suwannaporn, 2009).

Freeze drying can also be used to prepare quick cooking rice, and is accomplished by freezing the product, then decreasing the pressure of the environment, so that water sublimes directly from solid to gas (Singh & Heldman, 2001). After sublimation of the ice crystals, large pores remain and the freeze dried rice is more fluffy and spongy than hot air dried rice (Rewthong, Soponronnarit, Taechapairoj, Tungtrakul, & Prachayawarakorn, 2011) and the porosity of freeze dried rice at 0.04 mbar is higher than when dried at 1.25 mbar (Oikonomopoulou, Krokida & Karathanos, 2011). However, the mechanism how pressure affects porosity was not analysed in that study. An advantage of freeze drying rice is that it occurs below the glass transition of the polymer matrix and many of the subsequent storage effects on structure and texture related to water and polymer movement are retarded; this may also assist in the retention of small flavour molecules (Noel, Ring & Whittam, 1990). Quick cooking rice produced by soaking, autoclaving, then a combination of partial freeze drying and convective air drying was rehydrated with boiling water for 5 min and displayed well separated grains that were cooked to the core, were white and had no or slightly perceptible off-flavour compared to only air dried (Smith *et al.*, 1985); however, no comparison between quick cooking and freshly cooked rice was conducted. Both hot air drying and freeze drying have their disadvantages: the high temperature of hot air drying causes colour change and can degrade vitamins while freeze drying is an expensive, slow process that requires high energy consumption. A combination of air drying, microwave drying and an osmotic process using a glucose and sodium chloride solution to produce quick cooking rice showed improved colour and texture than that produced only with hot air drying or freeze drying (Chen, Qian, Zhang, Liu, & Lu, 2014). After rehydration, the quick cooking rice produced by the new process was rated more similar to freshly cooked rice in terms of flavour, whiteness, hardness and elasticity as measured by sensory analysis and instruments (Chen *et al.*, 2014). Thus, the use of new drying technologies and combinations of them may increase the quality of shelf-stable dried rice compared to traditional drying technologies although this may come at a significant cost.

2.3.4 Storage

When cooked rice is stored, gelatinised starch recrystallises to an extent dependant on time, temperature and moisture content and leads to changes in rice sensory properties (Piggott, Morrison & Clyne, 1991; Slade & Levine, 1987). During storage, starch retrogradation, measured as the change in enthalpy using differential scanning calorimetry, was reported to correlate positively with instrumental hardness and negatively with stickiness in cooked rice (Lima & Singh, 1993; Perdon, Siebenmorgen, Buescher, & Gbur, 1999). Retrogradation increases rapidly in the first 7 days of storage, as amylose recrystallizes rapidly, and then increases slowly after 14 days of storage as amylopectin recrystallizes slowly (Baik, Kim, Cheon, Ha, & Kim, 1997; Yu, Ma & Sun, 2010b). The increase in enthalpy is negatively correlated with storage temperatures above the glass transition temperature, resulting in an increase in hardness (Lima & Singh, 1993). The decrease in adhesion during storage was highest for high amylose rice, followed by medium and low amylose varieties (Lima & Singh, 1993).

To retard starch retrogradation in frozen rice it is recommended to store below the glass transition temperature because the unfrozen phase of a starch gel is maintained at a glassy state surrounding the ice, thus the mobility of molecules is reduced and diffusion limited properties are stable (Hsu & Heldman, 2005). Besides the storage temperature, the cooling rate also affects retrogradation. The study of Yu et al. (2010a) suggests a rapid cooling rate combined with a storage at -18 °C to retard starch retrogradation of cooked rice because a rapid cooling rate of 1.45 °C/min needs a shorter freezing time, thus starch molecules do not have time to reassociate compared to a slow cooling rate of 0.09 °C/min.

A process that delays starch retrogradation is HPP. Lower retrogradation as a function of storage time was shown for completely gelatinised rice starch suspensions treated at 600 MPa for 30 min compared to starch suspensions boiled for 30 min (Hu *et al.*, 2011). The delayed retrogradation was explained by the smaller amount of freezable water and a different recrystallization mechanism in HP treated starch, which is not fully understood yet (Doona, Feeherry & Baik, 2006). The amount of leached amylose in heat treated rice starch suspensions decreased from around 95 to around 15 % after one day of storage, whereas the HP soaked rice starch suspensions (100 – 600 MPa, 30 ºC) only leached ~5 % at the beginning and did not change throughout 35 days of storage because the HP treated starch granules kept their integrity (Hu *et al.*, 2011). A comparison between HP gelatinised non-waxy rice starch and waxy starch gelatinised under HP at ambient temperature showed no difference of retrogradation as a function of storage time, which supports the notion that high pressure affects amylose more than amylopectin (Hu *et al.*, 2011). The elastic modulus of HP induced gel was not sensitive to storage temperature (4 °C compared to 25 °C), whereas the elastic modulus of heat induced gel was higher at 4 °C (Douzals, Perrier Cornet, Gervais, & Coquille, 1998). The precise difference that these starch properties will have on cooked whole grains remains to be investigated.

Much work has been done on sensory and chemical analysis of flavour after raw rice was stored for a certain time and temperature and then cooked. However little is known about how cooked/convenience rice flavour changes with different storage conditions. If other ingredients are added to cooked rice, storage time and temperature are expected to lead to rancidity through oxidative degradation of lipids (Champagne, 2008; Piggott *et al.*, 1991). The addition of 15 % (w/w) sunflower oil to quick cooking rice after drying changed the fatty acid concentration and composition of aldehydes, ketones and alkenes compared to rice without added oil; and after a storage time of 4 months at 37 °C a significant change in these compounds occured which was expected to change the flavour (Semwal *et al.*, 1996). Unfortunately, no sensory analysis was performed to show if the change in fatty acids could be sensed by consumers. Since flavour is a decisive quality factor for consumers, its deterioration in convenience rice after storage should be understood.

Preventing retrogradation can decrease changes of cooked rice texture and can be achieved in different ways including storage at higher temperature, below the glass transition temperature or applying HPP. The retrogradation rate of stored frozen rice starch and HPP rice starch solutions was investigated, however, the effect of storage on texture or flavour of convenience rice such as retorted rice or quick cooking rice at different temperature remains to be investigated.

Post-cooking processes severely alter the sensory properties of convenience rice. To cool cooked rice, air-blast cooling is recommended by food processors to minimise moisture loss, and the higher cooling rate limits changes in hardness and adhesiveness. Frozen rice has similar texture compared to freshly cooked rice, when freeze-thawing can be prevented, however the influence on volatile compounds remains to be investigated. High temperature treatments increase the yellow colour and deteriorate flavour and should be minimised. Drying and freeze drying create a porous structure, leading to a spongy texture upon rehydration for quick cooking rice, which is generally perceived as inferior to freshly cooked rice. New technologies and a combination of post-cooking processes are being developed to reduce penalties of convenience to the sensory experience of rice consumers.

3 Conclusions and future perspectives

The current sensory deficiencies of convenience rice clearly show great potential for improvement. The quality of freshly cooked and convenience rice is strongly affected by each processing step it undergoes and by the addition of oil or starch cross-linking agents. Flavour deterioration in cooked rice is caused by the oxidation of surface lipids and the loss or change of volatiles, and the factors related are found in Fig. 2. The oxidation of surface lipids is largely defined by the accessibility of lipids to oxygen, therefore, storing the rice in oxygen accessible conditions or using processes, such as washing or soaking which remove lipids or add oil as an aid to processing will alter oxidation. Increases in molecular mobility result in the loss of some volatiles and this mobility is increased by processes which use temperature treatments above 100 °C such as drying or retorting, but can be prevented by freezing. High temperature treatments such as cooking, drying or retorting that occur at or above 100 °C also increase the yellow colour in rice due to Maillard reactions. The factors affecting rice colour change are summarised in Fig. 3 with the majority of colour change preventable by using processing treatments under 0 °C or preventing enzymatic browning. Beyond affecting the appearance and flavour of rice, temperature is an important mechanism in altering rice texture by enhancing starch retrogradation, starch mobility and water diffusion. These and other mechanisms affecting the hardness of cooked rice are summarized in Fig. 4. The hardness of cooked rice is reduced by increasing the size of pores within the rice by cooking it in excess water at temperatures above 140 °C, drying or through freeze-thawing. Increasing the moisture content of rice via increasing the W/R during cooking or soaking decreases the hardness of processed rice.

Conditions, such as storing of cooked rice below the gelatinisation temperature but above freezing temperature, allow significant polymer mobility over long periods of time increasing grain hardness. The stickiness of cooked rice is altered by changes of the surface of the rice grain, particularly amylose leaching and the loss of any starchy coating and is depicted in Fig. 5. When rice is washed, soaked or cooked in excess water, surface components such as starch molecules, protein and surface lipids are lost, while cooking by absorption retains the majority of these components creating a stickier starchy coating. The addition of oil or emulsifiers alters the grain surface decreasing the stickiness while drying and starch retrogradation alter the starchy coating decreasing stickiness.

The majority of current, frequently used techniques in rice processing alter the flavour and textural properties of rice through the interaction of several mechanisms. These mechanisms are: the elevation and reduction of temperature; the mobility of water and starch polymers; the creation of pores; and the addition or removal of components which result in colour and flavour changes.

As HPP is a non-thermal treatment it has great potential to improve convenience rice sensory by removing the detrimental changes to rice acceptability due to high temperature. The mechanism by which the HPP alters rice structure is poorly understood but some relationships have been observed. HPP shorter than 120 min without a subsequent cooking step does not gelatinise rice starch completely and leads to hard rice grains. Rice cooked after HPP reduces amylose leaching in rice soaking process and decreases hardness, indicating a decrease in polymer mobility. Differences in molecular mobility may similarly alter the volatile composition in cooked HPP rice with the loss of volatile compounds depending on pressure-temperature combinations. The mechanisms of HPP leading to stickier, and increased cooling rates leading to less sticky rice grains are not well understood yet. The changes may be due to a different effect of HPP on molecular mobility of starch molecules inside the grain compared to temperature treatments. Additionally, the influence of HPP on starch retrogradation in convenience rice under various storage conditions remains to be investigated.

Often only observations in changes of texture or sensory properties as a result of certain treatment conditions are reported, but the causation and mechanism between processing, kinetics, molecular changes and resulting quality, is missing. Therefore, further research is necessary to investigate how each processing step affects the structural, physicochemical and mechanical properties of rice, that ultimately lead to eating quality and sensory perception such as appearance, texture and flavour.

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Tables

Table 1. Processing methods in rice technology and their main effect on cooked rice quality.

Figure captions

Fig. 1. Pre-cooking, cooking and post-cooking technologies with different classifications to produce freshly cooked and convenience rice.

Fig. 2. Effects of processing conditions on cooked rice flavour deterioration, measured by sensory analysis and/or instruments.

Fig. 3. Effects of processing conditions on cooked rice colour, measured by sensory analysis and/or instruments.

Fig. 4. Effects of processing conditions on cooked rice hardness measured by sensory analysis and/or instruments.

Fig. 5. Effects of processing conditions on cooked rice stickiness. Stickiness includes adhesiveness and cohesiveness, measured by sensory analysis and/or instruments.

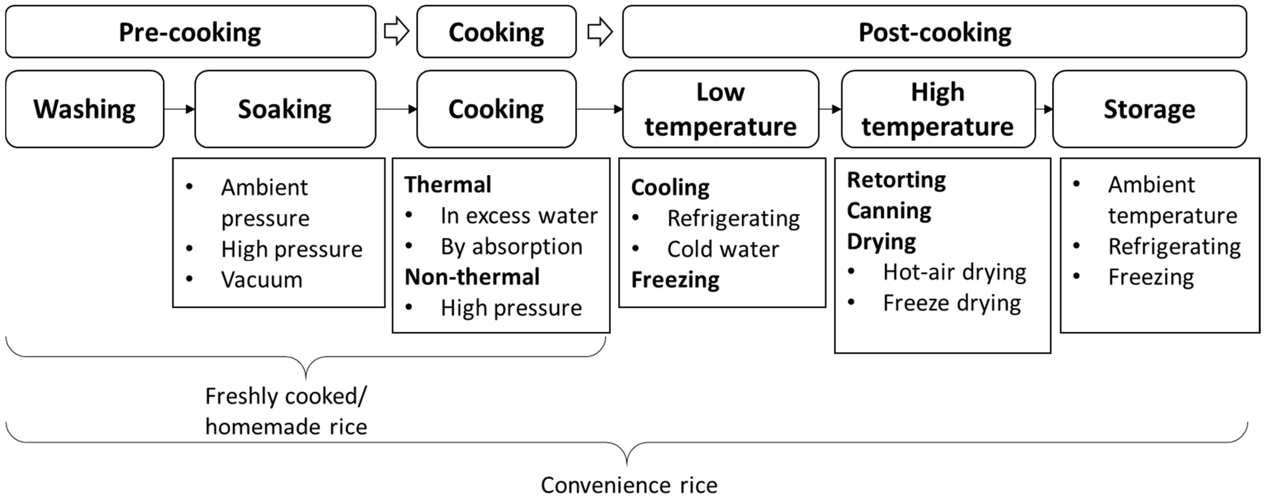
Table 2. Processing methods in rice technology and their main effect on cooked rice quality.

Table 2. Processing methods in rice technology and their main effect on cooked rice quality.

	Processing technology	Variation	Rice product	Effect on cooked rice quality	Reference
Pre-cooking	Washing	Washing step repetitions 2 – 5 times	Homemade rice	Washing steps remove surface lipids, leading to decreased off-flavour development after cooking and warm-holding.	(Champagne *et al.*, 2010; Fukai & Tukada, 2006; Monsoor & Proctor, 2002)
	Soaking	Ambient pressure	Homemade rice, high pressured rice, quick cooking rice, frozen rice	Improved complete gelatinisation due to uniform distribution of moisture in grain, produces/enlarges cracks. Leaching of solids, especially starch which influences texture. Compared to unsoaked samples: Increased hardness and decreased stickiness. Negative influence on flavour and sweet taste. Decreased cooking time and energy consumption.	(Chakkaravarthi *et al.*, 2008; Champagne, 2008; Chiang & Yeh, 2002; Das *et al.*, 2006; Genkawa *et al.*, 2011; Han & Lim, 2009; Horigane *et al.*, 2006)
		Vacuum		Hydration rate higher than soaking at ambient pressure. No difference in instrumental hardness, springiness or cohesiveness after cooking compared to soaking at ambient pressure.	(Bello Marcelo *et al.*, 2008; Tian *et al.*, 2014)
		High pressure		Hydration rate higher than soaking at ambient pressure. Partial gelatinisation at certain pressure, time, temperature combinations possible. Decreased instrumental hardness, increased instrumental springiness and cohesiveness. Increased glucose amount at 55 °C and improved whiteness after cooking.	(Bello Marcelo *et al.*, 2008; Tian *et al.*, 2014; Yamakura *et al.*, 2005a)
Cooking	Thermal cooking	Excess water	Convenience rice, homemade rice	Higher W/R increased sensory stickiness and decreased sensory hardness. Decreased stickiness and hardness for Basmati and long grain rice. Increased stickiness for Jasmine rice. Higher energy consumption compared to absorption method.	(Billiris *et al.*, 2012a; Chakkaravarthi *et al.*, 2008; Crowhurst & Creed, 2001; Das *et al.*, 2006; Mestres *et al.*, 2011; Meullenet *et al.*, 1998; Wada *et al.*, 2010)
		Absorption method	Homemade rice	Optimal W/R recommendations depend on amylose content. No uniform moisture distribution in bulk, thus difficult to apply in industry. Leached amylose and amylopectin interact with each other and form a coating on the surface of grains increasing stickiness. Increased stickiness and hardness, more acceptable flavour for Jasmine rice compared to cooking in excess water.	(Bett-Garber *et al.*, 2007; Crowhurst & Creed, 2001; Das *et al.*, 2006; Perez & Juliano, 1979; Srisawas & Jindal, 2007)
	Non thermal cooking	High Pressure	High pressured rice	Different gelatinisation mechanism compared to heat treatment. Decreased leaching of amylose and amylopectin compared to non HP treated. Starch granule integrity improved. Decreased hardness and increased cohesiveness after microwaving HP treated rice	(Boluda-Aguilar *et al.*, 2013; Buckow *et al.*, 2007; Deng *et al.*, 2013; Yamakura *et al.*, 2005a)

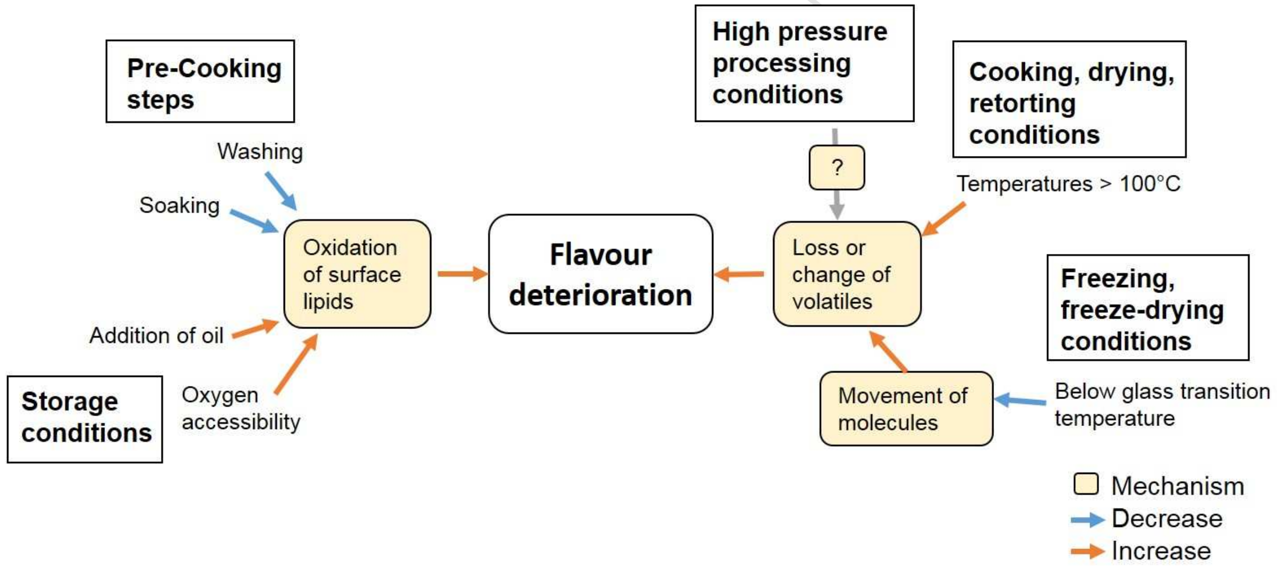
Alteration in volatile compounds, increased glucose concentration.

				compared to non HP treated rice. Alteration in volatile compounds, increased glucose concentration. Improved sensory acceptance compared to freshly microwaved rice.	
Post-cooking	Cooling	Air-blast cooling, cold room cooling, plate cooling, vacuum cooling, rinsing with cold water	Retorted rice, quick cooking rice, frozen rice	No change in moisture content with air-blast cooling, no influence on hardness. Increased instrumental hardness and cohesiveness using cold room cooling, especially at slow cooling rates. Decreased instrumental stickiness after rinsing with cold water due to washing away the starchy coating on the surface of grains.	(Hsu & Heldman, 2005; Ma & Sun, 2009; Meullenet *et al.*, 1998; Smith *et al.*, 1985; Yu *et al.*, 2010a; Zhang & Sun, 2006)
	Freezing	Air-blast freezer, cryogenic technology	Frozen rice	Rapid freezing retard starch retrogradation due to decreased damage of cellular structure, improved maintenance of textural properties.	(Tressler, 1968; Yu *et al.*, 2010b)
	Retorting	Sterilisation by retorting (112 – 125 °C)	Retorted rice	Deterioration of colour, flavour and texture due to excess heating. Increased sensory hardness and stickiness of retorted rice with added oil compared to freshly cooked rice.	(Kobayashi *et al.*, 1991; Ohtsubo *et al.*, 2004; Prakash *et al.*, 2005)
	Canning	Sterilisation by canning	Canned rice	Rice grains distorted and mushy due to excess water. Disintegration prevented by adding chemicals to cross-link starch.	(Alary *et al.*, 1977; Bergman *et al.*, 2004; Luh, 1991a; Ohtsubo *et al.*, 2004; Rutledge *et al.*, 1974; Rutledge & Islam, 1976)
	Drying	Hot air drying, tray drier, convective air drying, freeze drying, microwave drying or combinations	Quick cooking rice, instant rice	Production of porous structure for faster rehydration, but crumbly texture. Drying temperature > 100 °C increases yellowness, but does not affect shrinkage or rehydration capability. Increasing drying temperature increases hardness and chewiness of rehydrated quick cooking rice. Freeze drying increases porosity leading to fluffy texture. Combination of hot air drying and freeze drying improves colour, grain separation and flavour.	(Carlson *et al.*, 1976; Chen *et al.*, 2014; Luangmalawat *et al.*, 2008; Prasert & Suwannaporn, 2009; Rewthong *et al.*, 2011; Semwal *et al.*, 1996; Smith *et al.*, 1985)
	Storage	Room temperature	Convenience rice	Retrogradation of starch increases hardness and decreases stickiness. Rancidity due to degradation of added oil possible. High pressured rice retard starch retrogradation.	(Hu *et al.*, 2011; Lima & Singh, 1993; Perdon *et al.*, 1999)
		Below glass transition temperature	Frozen rice	Prevention of microbial growth.	(Hsu & Heldman, 2005; Yu, Ma, Zheng, Liu, & Sun, 2012)



Pre-cooking
Cooking
Post-cooking
Washing
Soaking
Cooking
Low temperature
High temperature
Storage
Ambient pressure
High pressure
Vacuum
Thermal
In excess water
By absorption
Non-thermal
High pressure
Cooling
Refrigerating
Cold water
Freezing
Retorting
Canning
Drying
Hot-air drying
Freeze drying
Ambient temperature
Refrigerating
Freezing
Freshly cooked/ homemade rice
Convenience rice

Fig. 1.



Pre-Cooking steps
Washing
Soaking
Addition of oil
Storage conditions
Oxygen accessibility
Oxidation of surface lipids
Flavour deterioration
High pressure processing conditions
?
Loss or change of volatiles
Cooking, drying, retorting conditions
Temperatures > 100°C
Freezing, freeze-drying conditions
Movement of molecules
Below glass transition temperature
Mechanism
Decrease
Increase

Fig. 2.

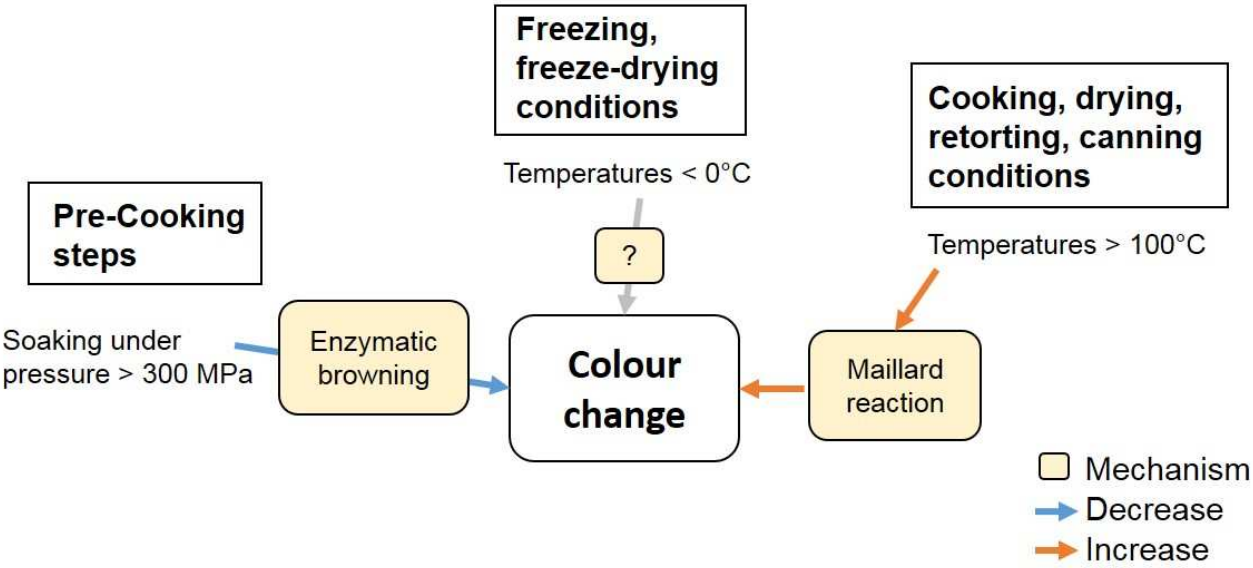

Freezing, freeze-drying conditions
Temperatures < 0°C
?
Cooking, drying, retorting, canning conditions
Temperatures > 100°C
Pre-Cooking steps
Soaking under pressure > 300 MPa
Enzymatic browning
Colour change
Maillard reaction
Mechanism
Decrease
Increase

Fig. 3.

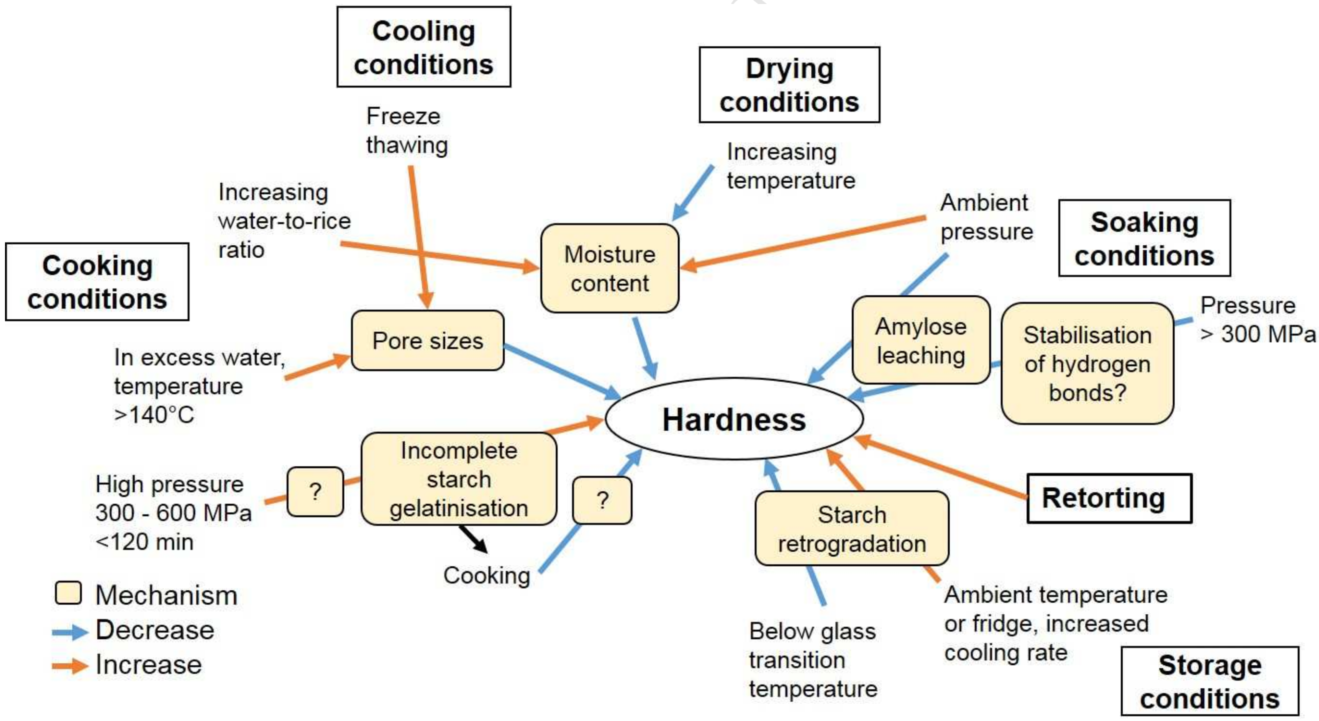

Cooling conditions
Freeze thawing
Drying conditions
Increasing temperature
Increasing water-to-rice ratio
Ambient pressure
Soaking conditions
Cooking conditions
Moisture content
Pore sizes
Amylose leaching
Stabilisation of hydrogen bonds?
Pressure > 300 MPa
In excess water, temperature >140°C
Hardness
High pressure 300 - 600 MPa <120 min
?
Incomplete starch gelatinisation
?
Cooking
Starch retrogradation
Retorting
Ambient temperature or fridge, increased cooling rate
Below glass transition temperature
Storage conditions
Mechanism
Decrease
Increase

Fig. 4.

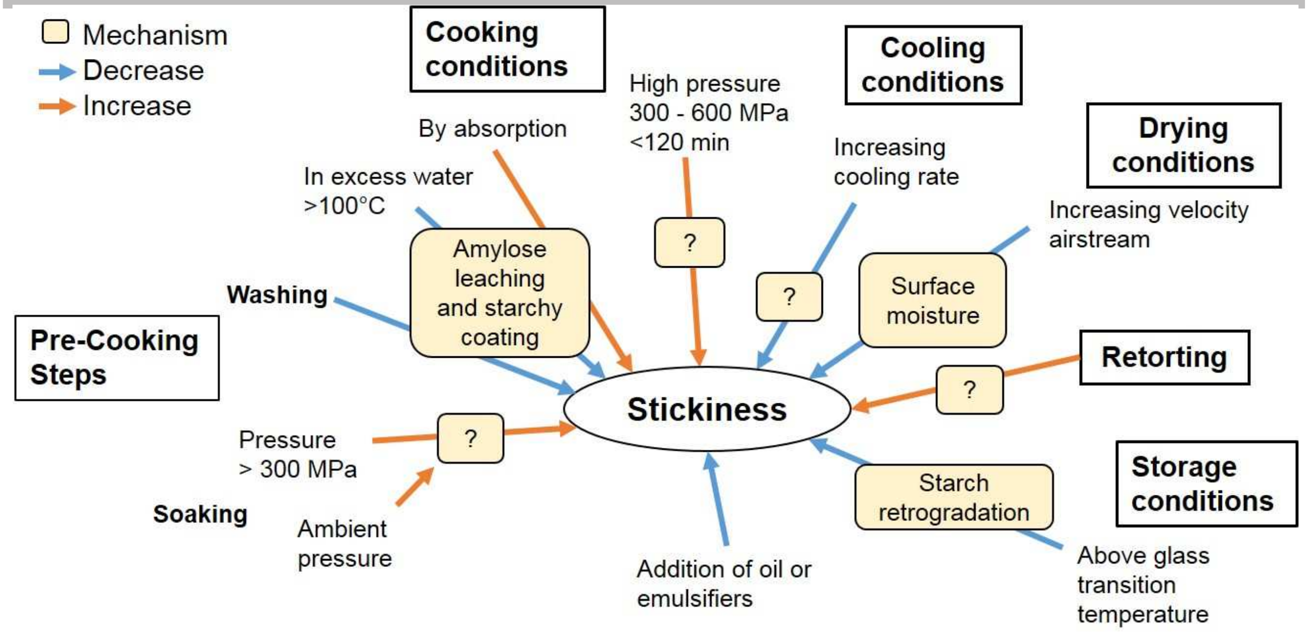

Mechanism
Decrease
Increase
Cooking conditions
By absorption
In excess water >100°C
High pressure 300 - 600 MPa <120 min
Cooling conditions
Increasing cooling rate
Drying conditions
Increasing velocity airstream
Washing
Pre-Cooking Steps
Amylose leaching and starchy coating
?
Surface moisture
Retorting
Stickiness
Pressure > 300 MPa
Soaking
Ambient pressure
Addition of oil or emulsifiers
Starch retrogradation
Storage conditions
Above glass transition temperature

Fig. 5.

Highlights

Processing related reduction of convenience rice quality is mechanistically explained.

Flavour deteriorates as volatile profiles are altered by thermal processes and storage.

Cooked rice texture is dependant on the rate and extent of water and starch diffusion.

Different mechanisms in high pressure processes may improve convenience rice quality.