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REVIEW ARTICLE

Rice quality improvement. A review

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Abstract

The value of rice to producers and consumers can be markedly increased by grain quality improvement. However, effective increase in the economic and nutritive value of rice can only be made with a better understanding of the conditions governing the production of rice with different grain types and quality and the control of quality along the value chain. This review examines the conditions governing the production of rice with price differentiated grain types and grades, with the aim to identify the limits and opportunities for quality and value upgrading. This begins with the production of Basmati and Hom Mali, the most expensive rice on global market, followed by a review of the effectiveness of rice breeding and management, and the roles of postharvest sorting and quality control, with the following conclusions. The production of rice with the highest price and quality is restricted by the eco-geographical limits. A substantial quality improvement has been achieved within each grain type through breeding, with grain quality as the key attribute differentiating modern high-yielding rice varieties that have become mega-varieties from those that have not. Due to the general preference for unbroken rice kernels, the value of rice is increased with grain breakage reduction at harvest and postharvest. The paddy from Asia's numerous small farms, with diverse ecological and socio-economic conditions, is required to be sorted into quality and price differentiated segments of the value chain, so providing the incentives to manage for quality. Incentives are also required for nutrient-enriched rice to be segregated from the non-enriched grain, to impact the nutrient intake of low-income rice consumers. Ambitious rice development strategies aiming to improve grain quality are effective and sustainable only with the recognition of key quality control processes, and the need for quality differentiating management along the value chain.

Keywords Basmati · Hom Mali · Jasmine · Nutrient enrichment · Thailand · Value chain

Contents

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1 Introduction

Yield improvement, recorded in the linear growth of the global rice yield at 51 kg per hectare per year from 1961 to 2017 in the FAOSTAT database (FAO 2019a), is undisputed evidence of a major achievement in modern rice science and technology. Rice quality improvement is, however, much more complex because of the different ways in which quality is defined by different groups of consumers. The view that farmers focus on the quality of the seed for planting materials and dry grain for consumption, while millers and traders pay attention to moisture content, variety integrity and milling recovery (Juliano 1993) is too simplistic and fails to reflect quality controlling feedbacks along the value chain. Commercialisation of rice production means that a farmer's decision relating to quality may be influenced by consumer preference in another part of the country or on the other side of the world. Throughout Asia, where most of the world's rice is grown and consumed, rice varieties are often recognised by their grain quality features

(Rerkasem and Rerkasem 2002; Appa Rao et al. 2006; Calingacion et al. 2014), along with their unique morphology and well-established local names that are generally used to identify local crop varieties or landraces (Brown 1978; Harlan 1992). Substantial price differentials among rice of different types and grades (FAO 2019b) and the premium prices for rice with the highest quality such as Thailand's Hom Mali (OAE 2017) and India's and Pakistan's Basmati (APEDA 2017) have stimulated interest and efforts in rice quality improvement (e.g. Efferson 1985; Unnevehr et al. 1992; Fitzgerald et al. 2009; Calingacion et al. 2014; Custodio et al. 2016; Feng et al. 2017). In addition to higher prices, the economic value of rice with a particular grain type can also be boosted by market expansion to satisfy new consumers.

Diversity in rice quality generally recognised has been confirmed in efforts to characterise rice quality in different countries and regions with inputs from local experts combined with determination of the physico-chemical properties of the grain (Calingacion et al. 2014). Interviews with consumers and other participants in the value chain provide insights into the perception of characteristics that contribute to the valuation of rice quality (Custodio et al. 2019). Characteristics thus reported to describe the best quality rice in Southeast Asia included nutritional benefits, softness and aroma, and in South Asia they were physical appearance of the grains (uniformity, whiteness, slenderness), satiety and aroma. The main types of grain actually produced, traded and consumed in each country and region are, however, more diverse in their quality. Softness and aroma are distinctive quality features of jasmine rice, but the rice produced and consumed in Southeast Asia is mainly non-aromatic, with jasmine rice being in the minority in Thailand (Rerkasem 2017), and accounting for an even smaller share in Southeast Asia as a whole. Whiteness and aroma clearly do not apply to parboiled rice, which accounts for most of the rice grown in South Asia and consumed by the majority population of the region (Bhattacharya 1985; Choudhury 1991). Parboiling, which involves steaming rice in the husk before milling (Fig. 1), produces yellowish tinted grain with its own unique scent and flavour, but not aromatic in the same sense as Basmati or jasmine. Although it has been pointed out that grain with less colour can be produced with modern parboiling mills (Custodio et al. 2016, 2019), parboiled rice in various shades of colouring are marketed under names such as 'gold', 'apple' or 'rose' to satisfy diverse customary preferences. As income rises, demand for rice with high quality is expected to grow (Unnevehr et al. 1992; Calingacion et al. 2014). However, in spite of their prices at double to triple the price of milled rice of ordinary types with lower grades, Basmati accounts for only 3% of India's annual rice production (APEDA 2017), Japonica one quarter of China's (Peng et al. 2009), and Hom Mali less than one third of Thailand's (Rerkasem 2017). While quality is an obvious concern in commercial rice production, it can be an important criterion that overrides advantages in yield and disease resistance in rice variety evaluation by those who grow rice for their own consumption (Rerkasem and Rerkasem 1984). This review examines the ecological and socio-economic conditions that have given rise to a diversity of rice types and price differentiated grades, highlighted by the genetic, environmental and management conditions for grain with premium quality and prices. Successes in quality improvements, with breeding and management at the farm and post-harvest, and in the sorting of rice with different grain types and grades from numerous small farms are described, with an emphasis on quality control along the value chain (Fig. 2). Opportunities and limitations to an improvement in nutritional quality of the rice grain with relevance to human and crop health are reviewed.

Fig. 1 Rice parboiling, by steaming paddy in the husk before milling, a common home processing in rural South Asia. Source: photo by P. Teng

2 The agro-ecological niche of rice quality

The rice grain that is universally consumed is the endosperm of a grass, *Oryza sativa* L., including in Africa where it has almost completely displaced the African rice, *O. glaberrima* (Nayar 2014). The agro-ecological niche of each grain type, i.e. the ecological and socio-economic conditions that determine the quality of the rice grain, is here reviewed. Indica is the eco-geographic group of rice varieties adapted to the tropics, while japonica is the group adapted to temperate environments (Mackill 1995; GRiSP 2013). These two main groups of varieties are sometimes classified as subspecies, as they are genetically incompatible, producing infertile hybrids when cross-fertilised (Oka 1957; Liu et al. 1996; Guo et al. 2016). Traditionally, the grain type of japonica rice is typified by the short and medium grain rice of Japan, Korea and northern China, with low amylose content giving it a soft and moist texture when cooked, while indica varieties are predominantly higher in amylose content, producing rice with a firm and dry texture when cooked. Dominance of indica or japonica type

Fig. 2 Paddy crushing, a simple procedure for quality control routinely practised by farmers, villagers and rice buyers in Thailand (left) and potential milling quality revealed in appearance of the grain inside the husk, degree of grain breakage, grain translucency or chalkiness, pericarp colour and presence of weedy red rice (right). Source: photo by B. Rerkasem

grain is reflected in the distribution of rice varieties from tropical and temperate countries, with some notable exceptions (Fig. 3). Most of the world's rice is non-glutinous, with more than 10% amylose, but most rice varieties in Laos, where glutinous rice is the staple, have 10% or less amylose. China's indica varieties that account for three quarters of the country's rice area (Peng et al. 2009) are closer to the rice of South and Southeast Asia in amylose content. In Thailand, rice varieties with 20% amylose or less are actually in the minority, while the grain is predominantly long and slender, as previously recorded (Rerkasem and Rerkasem 2002). The rice in non-traditional rice-growing countries such as the USA and Australia is more diverse, presumably to meet demand from their culturally diverse population and industries. Global rice production is dominated by indica, which makes up almost all of the rice grown in tropical South and Southeast Asia, as well as China's sub-tropical region. Indica rice is also exported in much greater volume than japonica, with export prices reflecting quality differences between the two types of grain, and also other factors such as price support, subsidy and tax policies (Fig. 4). This applies to exported rice from China, which implemented a food security policy restricting indica rice exports while allowing the export of higher priced japonica rice (Hansen et al. 2002). Indica varieties also account for more than 90% of the rice grown in India. Much of the remainder is made up of Basmati (APEDA 2017), the premium priced aromatic rice that has been shown to be genetically closer to the japonica group of varieties by molecular analysis (Kovach et al. 2009).

Diversity of rice grain types and grades in Thailand, where quality benchmarks for jasmine and non-aromatic rice have been set, exemplifies the way in which each is determined by its agro-ecological niche. With 98% of rice areas located between the latitudes 12° and 20° N, Thailand's numerous local rice varieties or landraces and modern, high-yielding varieties belong to the indica group. The exceptions are tropical japonica varieties grown for subsistence in the highlands (Jamjod et al. 2017) that account for some 0.5% of national production (Dumrongkiat 2013; OAE 2014). Following the development of modern high-yielding varieties that took off in the 1970s, rice in Thailand is grown from two plant types, but with five main types of grain recognised by consumers and the market, with further variation by grade or source covering the price range within each type of grain (Table 1). The spatial distribution of the rice with different plant and grain types is described by local preference for a specific type of grain as well

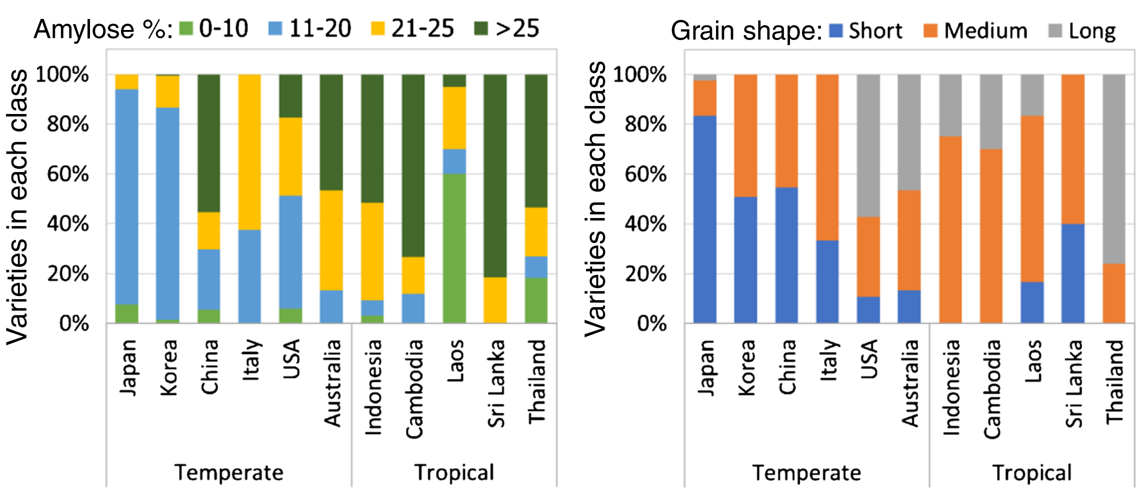

Fig. 3 Frequency distribution of rice varieties with different amylose content (left) and grain shape by length to width ratio of milled grain: short, < 2; medium, 2–3; long, > 3.0 (right), from selected temperate and tropical countries, where the common varieties are japonica and indica, respectively. Source: drawn with data from Juliano and Villareal 1993

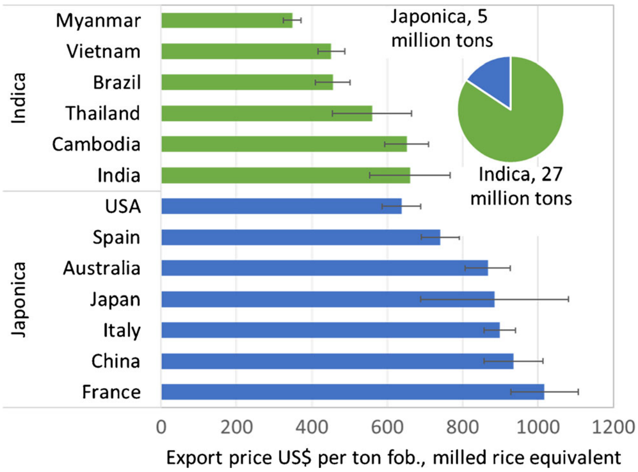

Fig. 4 Average price of rice from selected exporters of mainly indica (■) and japonica (■) type of grain (left) and relative export volume of the two types (right). (Prices are means for 2011 to 2016, with standard deviation). Source: drawn with data from FAO 2018

as the environmental condition controlling crop growth, yield and grain quality (Fig. 5).

The main rice crop in Thailand, grown in the wet season with a water supply from the monsoon rains, is composed of mainly traditional photoperiod-sensitive varieties with tall plant type. Modern, photoperiod-insensitive high-yielding varieties are grown with irrigation, which cover a quarter of the country's rice land where an extra crop is grown in the dry season in addition to the wet season crop, and sometimes continuously with 2.5–3 crops per year. With a 50% higher yield per crop than the rainfed crop of traditional varieties, the irrigated modern varieties account for half of the country's annual rice production from 40% of the crop area. Sometimes similar types of grain produced from photoperiod-sensitive traditional varieties are priced higher than the grain from modern varieties (Sommut 2003), although the distinction is less noticeable for the lower grades. The role that social and economic considerations play in determining rice quality is indicated by consumers' preference and the choice for grain of specific type and price range. This is shown by enduring traditional preference in the north and northeast for glutinous rice and in the central plain and other parts of the country for non-aromatic non-glutinous rice with a firm dry texture when cooked, while economic consideration is the primary criterion in choosing rice for those with limited income (Rerkasem 2017). Grain with higher amylose content absorbs more water, resulting in a greater volume expansion ratio (Juliano 1993), i.e. the volume of cooked rice relative to its precooked volume (Hussain et al. 1987; Mohapatra and Bal 2005). The perception that a larger volume of cooked rice is produced from the same amount of raw grain of certain grain types complements the lower price as the economic consideration in the choice of rice for those who wish to economise their rice expenditure. On the other hand, the parboiled rice export of some 3 million tons (TREA 2019), which is processed largely from the grain of modern high-yielding varieties with high

Table 1 Different types of rice produced in Thailand, their prices and contribution to the annual production

Plant type, grain type[1], variety and specifications	Price (THB kg^{-1})[2]	% Paddy production[3]
1. Photoperiod-sensitive varieties with tall plant type; some deep-water and floating rice varieties; grown in wet season only (61 ± 4% area[3])		49.6 ± 5.6
1.1 Hom Mali: aromatic with low amylose, grown from the variety KDML105 plus 7–8% from the variety RD15 (previous season crop 10–15% higher price than newly harvested)	28–32	25.2 ± 3.6
1.2 Non-glutinous, moderate to high amylose, local and local improved by pure-line selection, unspecified varieties[4] (varieties with exceptional quality 10% higher price than modern varieties)	10–12	4.7 ± 0.8
1.3 High-quality glutinous, aromatic when newly harvested, grown from the variety RD6 (north-eastern grown 15–20% lower price than northern grown)	26–30	16.9 ± 1.2
1.4 Glutinous, unspecified varieties[4] (10% lower price for short grain than long grain)	21–24	1.7 ± 0.4
2. Modern high-yielding, photoperiod-insensitive varieties; grown in wet and dry season or continuously, with irrigation (39 ± 4% area[3])		50.4 ± 5.6
2.1 Non-glutinous, moderate to high amylose, unspecified varieties[4]	10–12	38.0 ± 3.9
2.2 Jasmine: aromatic, low amylose almost all grown from PTT1 variety	20–24	7.8 ± 0.5
2.3 Glutinous, unspecified varieties[4] (10% lower price for short grain than long grain)	21–24	12.3 ± 3.0

[1] Amylose content and cooking quality: 0–2%, glutinous; low 10–19%, soft and moist; moderate 20–25%, dry and firm but not hard; high 26–35%, firm and hard (TRKB 2019a)

[2] Local prices of milled grain, sold in 100-kg bags, range by specification in grade, source, etc., adapted from Rerkasem 2017

[3] Average for crop year 2008/2009 to 2016/2017 ± standard deviation, data from OAE 2019

[4] Little distinction between traditional and modern varieties in their grain quality and price

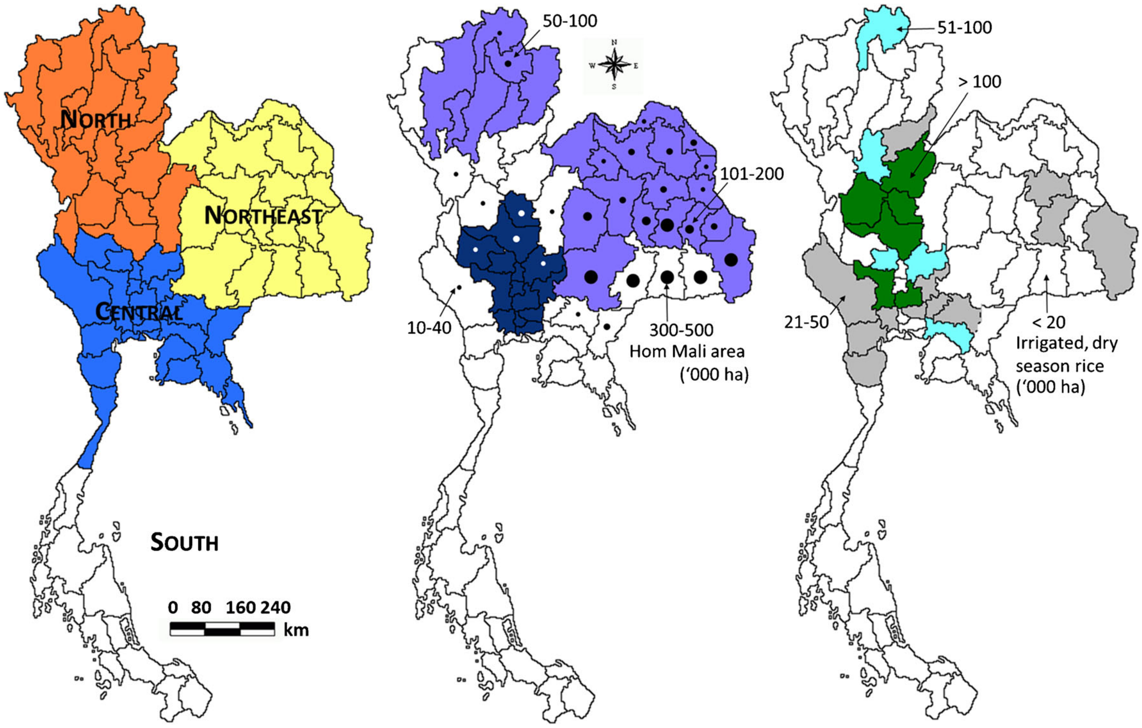

Fig. 5 Thailand's agricultural regions (left), ■ main glutinous rice producing and consuming provinces, ■ area with traditional preference for rice with dry firm texture when cooked, with Hom Mali area by province, indicated by size of circle: no circle, less than 10 thousand ha; largest circle, 300–500 thousand ha (centre), and irrigated, dry season rice area by province: □ less than 20 thousand ha; ■ 21 to 50 thousand ha; ■ 51 to 100 thousand ha; ■ more than 100 thousand ha (right). Source: modified from Rerkasem 2017, with data for 2016/7 growing season from OAE 2019

amylose, enabled Thailand to increase its market share of the global rice trade from 18 to 24% (computed from data in OAE 2017). This is in spite of the fact that, unlike in South Asian countries where there is a wide-spread tradition for parboiled rice consumption (Bhattacharya 1985; Choudhury 1991), parboiled rice is little known in Thailand except among those involved with its production and export.

Hom Mali, the premium quality and priced aromatic rice of the jasmine type, is required by law to be produced from the traditional photoperiod-sensitive varieties KDML105 and RD15, which are grown in the wet season only (TMOC 2016b). RD15, developed from KDML105 by mutation breeding and matures 10–15 days earlier (TRKB 2019b), is grown in areas with a shorter monsoon season, and accounts for less than 10% of the Hom Mali production. Approximately 35% of the annual production of Hom Mali rice is exported (computed from data in OAE 2017, 2019). Registration of Hom Mali, and Thai Hom Mali in some cases, as trademarks in importing countries (DFT 2011) provides legal protection against competition from other producers. In the domestic market, where Hom Mali of the highest grades are retailed at three or more times the price of ordinary, non-aromatic grain, it is clearly not the rice of choice of those who wish to save money when buying rice. Although KDML105 can be grown throughout the country, the bulk is produced in a relatively small area in the lower part of the Northeast (Fig. 5), where the grain is recognised by the market to have the highest Hom Mali quality, and priced accordingly. In neighbouring Cambodia, economic gains are being realised from the country's own varieties with traditional plant type, especially Phka Malis and Phka Rumduol, with the quality of the jasmine type grain approaching and sometimes surpassing Hom Mali (IFC 2015; Vent et al. 2015; Vannak 2017). Although the yield of Hom Mali can be increased with irrigation and fertiliser, production is limited by the inverse relationship between quality and yield (Suwanarit et al. 1996). The distinctive aroma, based primarily on the compound 2-acetyl-1-pyrroline (Buttery et al. 1983), is under the control of *badh2.1* gene (Kovach et al. 2009), but the strength of the aroma in the grain is highly dependent on the environment and management (Efferson 1985; Yoshihashi et al. 2002, 2004). In addition to intensity of the aroma, premium quality Hom Mali rice is also described by the physical attributes of the grain, including resistance to milling breakage, whiteness, translucency and the gloss of the milled grain (Leesawatwong et al. 2003). Since mutation of KDML105 caused by gamma irradiation that resulted in the variety RD15 also produced the high-quality glutinous variety RD6 (TRKB 2019b), these three genetically closely related varieties together account for 55% of the main season rice area (computed from data in OAE 2019).

Similar ecological, market and regulatory conditions are imposed on the production of Basmati rice in India and Pakistan, which combine to restrict the area where it can be grown to the Indian and Pakistani Punjab, and the Indian states of Jammu, Haryana, Uttaranchal and Western Uttar Pradesh (Indian Department of Commerce 2012), all locating above the latitude 27° N. Consumer choice of a particular type of grain may be an enduring tradition, e.g. parboiled rice consumption in South Asia that has continued since ancient time (Choudhury 1991) and the preference for glutinous rice as the main staple in Laos, northern and north-eastern Thailand and certain groups of ethnic Dai or Tai people in northern Myanmar and south-western China (Schiller et al. 2006; Falvey 2010; Sattaka 2016). Preferences and tastes, however, may also change over time. Historical shifts in the common grain type of rice in Thailand were recorded in old temple bricks, which employed the rice husk for reinforcement, with the presence of round and large grain types before the eleventh century, the disappearance of the large grain type from the lowlands after that, and since the eighteenth century an increasing prominence of the slender grain type (Watabe et al. 1970), which has become the norm in the present (Rerkasem and Rerkasem 2002). The shift in people's taste over a shorter time frame can be seen in the rapid growth in demand for rice from former non-rice consumers, e.g. China's wheat consumers who are consuming more rice following their migration to the city (Hansen et al. 2002). The growing demand for rice in Africa (Wailes and Chavez 2012; Demont and Ndour 2015) may be partly explained by displacement of the African rice *O. glaberrima* by *O. sativa* (Nayar 2014), although it is not known how much of the increase is due to changes in the eating habits of non-rice consumers and how much is due to the growing population of Asian immigrants and migrant workers.

3 Quality improvement through breeding and management

Although the production of rice of certain grain types (e.g. Hom Mali and Basmati) is constrained by eco-geographical limits, the quality attributes of each type of grain have nevertheless been upgraded through breeding and management, on-farm and postharvest. Long before definitive measurements were ever taken, and the genetic or physico-chemical bases explained, specific traits of the rice grain had been selected for those features that could be perceived by the senses such as grain size and shape, physical appearance of the endosperm, aroma and texture of the cooked rice. By the early twentieth century, milled rice from Siam (as Thailand was then known) was differentiated into different grades and from the rice of neighbouring countries by its long slender grain, and other notable physical appearance. "Siam rice is characterized by having a long, thin grain, the best qualities are more or less translucent, while lower qualities have a more or less opaque white spot on the belly of the grain. Burmah has a short thick grain, and it is all white and opaque. Cochinchina rice is not so thick and white as Burmah rice, but not as translucent as Siamese." (Sanitwongse 1988). Reflected in the variety names of local varieties are quality features that have been selected for, e.g., the word fragrance or the name of a sweet-smelling flower for aromatic varieties, words to distinguish endosperm starch type for glutinous and non-glutinous grain (Titiprasert et al. 2001; Appa Rao et al. 2006). New varieties continue to be developed by the international and national rice breeding programmes in various countries, but the final say in quality acceptability of new varieties apparently rests with consumers and the market, as demonstrated by persistent popularity of older rice varieties. The premium quality short grain japonica rice is still grown in Japan from Koshihikari released in 1953 (Blakeney et al. 2001; Kobayashi et al. 2018). More than 90% of Hom Mali rice is produced from KDML 105, developed by a pure line section of a farmer's rice seed in the 1950s (TRKB 2019b). PTT1, the only modern, photoperiod-insensitive, high-yielding aromatic variety with jasmine type grain that has found acceptance in Thailand, and priced at 75–80% of Hom Mali (TREA 2019), accounts for less than 10% of the country's aromatic rice production and export (OAE 2019). This is in spite of its yield at almost twice that from KDML105 and an insensitivity to photoperiod allowing it to be grown in dry as well as wet season (TRKB 2019b).

More successful is India's Pusa Basmati 1121, released in 2003, which combined photoperiod insensitivity and higher yielding capacity of modern rice varieties with traditional quality features of Basmati rice that include the unique grain elongation when cooked as well as the aroma (Singh et al. 2018), and accounts for 70% of the country's Basmati rice production (APEDA 2017). The value of India's rice crop has been substantially increased by the production of Basmati, which is exported at up to almost triple the price of non-Basmati grain and contributes to 60% of the country's rice export earnings from 35% of the volume (computed from data in APEDA 2017).

Highly satisfactory grain quality has clearly played a major role in wide adoption of certain modern high-yielding, non-aromatic varieties from international and national rice breeding programmes. With comparable traits for adaptation and pest and disease resistance, grain quality is the key attribute differentiating modern high-yielding rice varieties that have become regional and national mega-varieties from those that have not. One of these is IR64, which had spread over 10 million ha in Africa, South and Southeast Asia at the turn of the millennium (Mackill and Khush 2018). The popularity of IR64 was attributed to its grain quality, considered excellent for eating (Champagne et al. 2010), and parboiling. The name IR64 is regularly invoked at e-commerce sites offering not only parboiled rice but also parboiling mills for sale. The few modern high-yielding varieties, from some 50 varieties released since 1969 (TRKB 2019b), that now account for half of Thailand's annual rice production (Table 1) had also apparently satisfied the stringent quality standards to meet demand from different groups of rice consumers in the domestic and export markets, with glutinous as well as non-glutinous grain type with low to moderate and high amylose. Further progress in breeding to improve rice quality can be expected from identification of relevant genes and quantitative trait loci involved (e.g. He et al. 1999; Aluko et al. 2004). Nevertheless, the environment and management are still expected to play a major role in determining rice grain quality, particularly for rice with the highest quality and prices.

Field management with the largest impact on rice quality is probably the crop harvesting. The rice crop reaches maturity with the paddy moisture content (weight of water as percentage of paddy weight) at 20–25% (IRRI 2015; TRKB 2019a). Where rice is manually harvested, the crop is cut and allowed to dry towards the moisture content of 14–15%, which is considered optimum for paddy milling and storage (IRRI 2015), and to facilitate the separation of the grain from the straw in hand threshing. Combine harvesting, an increasingly common feature of modern rice farming throughout Asia (Reardon et al. 2014; Haefele and Gummert 2016), contributes to improving rice quality by enabling rice to be harvested when the paddy moisture content is still as high as 25% or higher. A timely harvest is also crucial to prevent the grain from becoming too dry and brittle, e.g. when the harvest is delayed by labour shortage, with detrimental effects on head rice yield (Siebenmorgen et al. 2007). Sun drying rice in the tropical summer may also expose the grain to extremely high temperature with adverse effects on quality (Haefele and Gummert 2016). Contamination from soil, sand and other impurities is common in sun drying, especially when it takes a long time during wet weather. However, while much more rapid and labour saving than the manual rice harvest, combine harvesting without appropriate post-harvest management can instead have largely negative effects on rice grain quality, with a severe milling breakage when the paddy with high moisture content is milled and spoilage by fungi when put in storage. Indeed, rice prices in Thailand were observed to suffer record plunges in 1992–1993 due to poor grain quality as the result of sudden large-scale adoption of combine harvesting in response to labour shortages without suitable post-harvest management (Thepent and Chamsing 2009).

Development of highly efficient small- to medium-sized modern rice mills that process 0.5–20 tons of paddy a day has enabled commercialisation of local rice varieties with limited production volume to serve the community or special quality rice, e.g. rice with pigmented pericarp, organic rice or 'sushi' rice, to directly supply restaurants, retailers in the city or overseas (Rerkasem 2017). For milled or white rice, the form of rice most commonly traded in the retail market and consumed, unbroken grain is almost universally preferred (Unnevehr et al. 1992) and is consequently priced higher than the grain that is broken into small fragments. An exception to this generalisation can be found in certain parts of Africa, including urban centres in Senegal, Gambia and Mauritania where a preference for broken rice has developed (Rutsaert et al. 2013), so the price differentiated grades are also applied to broken rice. Broken jasmine rice is regularly imported by Senegal, Côte d'Ivoire and Ghana (Mohanty 2015) at a considerably higher price than ordinary broken rice, but lower than unbroken jasmine. The standard for unbroken grain is called 'head rice', defined as the rice kernel that retains at least 75–80% of its original length (IRRI 2020). Resistance to grain breakage, the fundamental basis for head rice yield, is strongly influenced by environmental conditions in some rice genotypes but is more stable in others. In some rice varieties, head rice yield is low when nitrogen supply is low, and increases with nitrogen fertiliser application, while others, e.g. Starbonnet (Borrell et al. 1999), IR22 (Seetanun and De Datta 1973) and KDML105 (Leesawatwong et al. 2005), were identified as having high head rice yield even with a low nitrogen supply. In Thailand, the wet season crop generally produces rice with a higher head rice yield than the dry season crop, while the variety RD21 was identified as having a consistently high head rice yield regardless of the growing season (Laenoi et al. 2018). Where the price that farmers are paid for their paddy is based primary on the head rice yield (Leesawatwong et al. 2003), the cost of milling breakage may be borne mostly by farmers, who are paid lower price for head rice yield lower than the standard of approximately 40%. Higher head rice yield of up to 60% is an important source of profit margins for the mills, but is not translated into higher price for farmers, while the paddy with a 20% or lower head rice yield is relegated to the status of feed grade rice, with a fraction of the price of food rice (Prom-u-thai 2010).

The technology is available for producing 'good' quality rice at the farm, and yet efforts to boost rice production, in Africa in particular, often face stiff competition from imports due to the miss-matching of the definition of rice quality according to urban consumers and insufficient attention paid to post-harvest management in the transfer of rice technology (e.g. Demont and Ndour 2015; Demont and Rizzotto 2012; John 2015; Fiamohe 2017).

4 Sorting and quality control along the value chain

In Asia where most of the world's rice is produced, rice is grown by numerous small farms with widely different ecological and socio-economic circumstances. The sorting of rice and post-harvest management are of paramount importance to quality control. In the absence of sorting to segregate the rice of different grain types and grades, loads of paddy with heterogeneous quality are bulked together to be processed into milled rice of inferior grade, with no reward for either farmers or mills to manage for grain quality (Demont and Rutsaert 2017; Ba et al. 2019). Interviews with paddy buyers, mill operators and farmers in Thailand revealed how the paddy market can operate as a place for sorting rice from the multitude of farms into different types, grades and prices, for segregated processing, storage and marketing, while signalling back to inform farmer's decision on the choice of variety, type of rice and other farming management decisions in the next season (Rerkasem 2007; Prom-u-thai 2010; Rerkasem 2017). The sorting process begins with the price paid to farmers according to the type and quality of their paddy harvest, followed by separate processing, storage, transportation and trading of rice with different types and grades. The key arbiters at this sorting are the paddy buyers, who are either employed by mills and paddy assembling places or operate as independent itinerant traders who provide the bridge between the smaller farms and large buyers. A set of skills possessed by the paddy buyers includes the ability to quickly distinguish among the mega-varieties by some small physical markers, e.g. with a half-millimetre difference in grain length, a slight difference in the hue of the husk colour, and the nose for detecting variation in the intensity of the aroma in Hom Mali area. The mega-varieties that make up the bulk of the country's annual rice harvest are generally well recognised by name. However, the strong interaction effects of genotype and environment (G × E) mean that the grain produced from the same variety may vary considerably in quality and price. Precision and transparency in the quality evaluation and price setting are aided by simple tools such as moisture meters, sample mills and iodine (in tincture of iodine from the first aid kit) for rapid quantification of the presence of amylose in non-glutinous and glutinous grain admixture, in areas where the two types of grain are grown together in neighbouring fields or in the same field in succeeding seasons.

Moisture content is a major determinant of the paddy price in most countries (Unnevehr et al. 1992), but with different implications for the paddy designated as dry (moisture in the vicinity of 15%) and fresh or green (20% or more moisture, of combine harvested rice). For a dry paddy, the moisture content evaluation helps to ascertain if some drying is required before the rice can be safely stored or milled, but the price that farmers are paid is determined primarily by the potential milling quality. Traditionally this is carried out by crushing a small pile of paddy under a roller on a rough surface, to reveal the appearance of the endosperm underneath the husk and the presence of contaminants such as red weedy rice and glutinous grain as well as resistance to grain breakage (Fig. 2). Now this is often done quantitatively, rapidly, and more efficiently in sample mills that process approximately 100 g paddy samples by removing the husk to produce brown rice (endosperm with intact pericarp and embryo). In some types of mills, the samples are further processed by the polishing action (milling) to produce milled or white rice (endosperm without embryo, pericarp, and some of the aleurone layer). In the case of a fresh paddy destined for the dryer or parboiling mill, an assessment of the potential head rice yield is unnecessary as well as impractical, as the grain will all largely disintegrate when crushed or milled at this stage.

In spite of the high moisture content, the quality of a combine harvested fresh paddy is actually improved when followed with mechanical (or artificial, with heat sources other than direct sun energy) paddy drying or parboiling. The moisture content of fresh paddy can be rapidly and efficiently reduced by mechanical drying to the optimum level that produces maximum head rice yield when milled (Siebenmorgen et al. 2002; Thepent and Chamsing 2009; Fukai et al. 2019). The parboiling process, in which the rice grain is strengthened by the fusing together of starch grain in the endosperm when the paddy is cooked by steaming before milling (Bhattacharya 1985), also adds value by increasing head rice yield. For rice with a long slender grain, the typical milling yield of paddy that has been parboiled is 58% head rice plus 7% broken, compared with the yield of 39% head rice plus 26% of broken from the milling of the raw paddy (Siamwalla and Na Ranong 1990). The remaining 35% of the paddy weight is made up mainly of the rice husk and a small amount of bran, a product of rice milling containing embryo, pericarp, and some of the aleurone layer. Development of efficient burners has turned the rice husk, which used to have a negative value due to the disposal cost, into biofuel for rice driers, mills, parboiling mills and other industries. The 26% increase in the fat content of the rice bran by parboiling reported in Sri Lanka (Palipane and Swarnasiri 1985) probably explains the considerably higher price of the parboiled bran than raw bran where rice bran oil extraction is a common practice (Rerkasem 2017). Mechanical paddy drying, economically powered by burning the rice husk, has been rapidly adopted by rice mills and paddy assemblers, but not by farmers in Thailand in spite of the dryers built for them by government grants (Thepent and Chamsing 2009). A plausible explanation might be found in the convergence of fresh paddy prices when adjusted to the same moisture content; i.e. fresh paddy price differentials are accounted for largely by the weight of water. Furthermore, the urgent need for cash, e.g. to service loans, coupled with the lack of a storage facility, compels farmers to sell their paddy as soon as it is harvested, which unfortunately is the time when paddy prices drop to their lowest following the main harvest season.

The importance of milling breakage resistance to the quality and value of rice is indicated by the designated grades of milled rice in the market, as in Thai 100%, India 25%, Vietnam 5%, or US Long grain #2, 4% (FAO 2019b). However, it should be noted that the numbers do not represent any specific measurement, with 100% being the highest grade, followed by 5%, 10%, 15%, and 25%, in that order. The composition of the grain in each price differentiated grade of Thai rice, which is regulated by law (TMOC 2016a, b, c), is based on grain length and allowable breakage (Table 2) and the maximum limits for blemishes, imperfections and impurities (Table 3). Rice kernels that fail to reach the standard size for each variety may be produced by sub-optimum conditions during the growing season (Laenoi et al. 2018), as well as by a premature harvest (Siebenmorgen et al. 2007). The grains that fail to develop fully may become a value-depressing contaminant of milled rice, by being incompletely milled, remaining green or becoming discoloured. Yellow grain (colloquially called rat's tooth rice) is milled rice grain with a yellowish colour associated with fungal infestation that flourishes in rising temperatures when paddy with high moisture content is stored (Phillips et al. 1988; Gras et al. 1989; Bason et al. 1990; Duangsrisai 2012). Other grade-lowering contaminants are presence of the unhusked grain, chalky grain, weedy rice with red pericarp, and an admixture between glutinous and non-glutinous kernels. Grain chalkiness, an opaque area in an otherwise translucent background of milled non-glutinous grain, is considered objectionable, where translucency is a highly valued feature of milled rice including jasmine rice. The term chalky is applied to the somewhat opaque endosperm of Basmati (Juliano and Villareal 1993; Bhattacharjee et al. 2002), but with an opacity (not as dense as in the glutinous grain) evenly distributed over the entirety of individual grains. Uneven chalkiness is also unacceptable in high-quality Basmati.

For a given type of grain, there are considerable opportunities for increasing the value of rice. These include sorting and quality control measures along the value chain, particularly in the midstream segment (i.e. paddy trading, milling and parboiling). Economic incentives are the driving force by which rice with different quality attributes from numerous small farms are sorted in the paddy market, processed and maintained in distinct segments of the value chain until reaching consumers.

5 Nutritional quality for human and crop health

In spite of the perception that vitamin and mineral contents constitute a quality characteristic of rice with the highest quality (Custodio et al. 2019) and extensive documentation of their health benefits, there is no evidence that nutritional content plays a role in the actual valuation of the rice grain by farmers, consumers and the market. Nutritional quality of rice, defined by the content of elements or compounds with health implications, is not readily perceived by the senses and can only be determined with instrumentation. A notable exception is the bright yellow, beta-carotene-rich golden rice, which was reported as approaching production at the end of 2019 in Bangladesh (Dunphy 2019) and the Philippines (La Page 2019). The rice grain has the lowest concentration of iron (Fe) and zinc (Zn) among the main staple crops (Bouis and Welch 2010). The grains of Thailand's mega-varieties, for example, are substantially lower in Fe and Zn concentration compared with some less commonly grown varieties (Saenchai et al. 2012). This has contributed to the low intake and a deficiency in these micronutrients in a substantial share of the world's rice consumers (Welch and Graham 2002). In addition to Fe and Zn deficiency, other nutritional aspects of rice quality with health implications for rice consumers that have been identified include the low contents of protein (i.e. nitrogen, N), selenium

Table 2 Specification of grain length and price differentials in Thailand's exported white rice of different designated grades

White rice grade designation[1]	Price (US$ per ton, mean for 2013 to 2017 ± standard deviation)		Grain length requirement[2]		Full grain (minimum length of most of remaining grain fractions in brackets)[3]
			Long grain Class 1	Allowable short grain	
			Minimum, in % by weight		
100%A	463	± 68	70	5	60 (8/10)
100%B	437	± 56	40	5	60 (8/10)
5%	424	± 54	20	10	60 (7.5/10)
10%	419	± 53	10	15	55 (7/10)
15%	415	± 54	5	30	55 (6.5/10)
25%	405	± 55	Not specified	50	40 (5/10)
Broken[4]	378	± 68	Not specified	Not specified	15 (5/10)

[1] The numbers do not directly correspond to any specific measurement, although 100% is the highest grade with A being higher than B, for the grades from 5 to 25%, the lower numbers indicate higher quality, as can be seen from the price differentials

[2] Long grain class 1 is longer than 7 mm; short grain is shorter than 6.2 mm

[3] Full grain milled rice is at least 9/10 of intact grain length, with allowable minimum length of the remaining grain fractions in brackets

[4] Designated white broken A1 super special, similar in other physical quality features to the 100% rice

Source: description of the white rice grades in TMOC 2016c; price data from TREA 2018

Table 3 Legal quality standards for allowable contamination in Thai rice of selected types and grades

	Allowable contamination (maximum limit, in % by weight, or as indicated)		
(a) White rice, by designated grade	100%[1]	5%	25%
Red rice or incompletely polished kernels	0.5	2.0	7.0
Yellow kernels	0.2	0.5	1.0
Kernels damaged by mould, insects, etc.	0.25	0.25	2.0
Immature, incompletely filled grains, other impurities	0.2	0.3	2.0
Chalky kernels[1]	3.0	6.0	8.0
Glutinous kernels	1.5	1.5	2.0
Unhusked grains (paddy), number of grains in 1 kg	5	8	20
(b) Aromatic rice, by type and designated grade	Hom Mali		Jasmine
	100%	10%	100%
Red rice or incompletely polished kernels	0.5	2.0	0.5
Yellow kernels	0.2	1.0	0.2
Kernels damaged by mould, insects, etc.	0.25	0.5	0.25
Immature, incompletely filled grains, other impurities	0.2	0.4	0.2
Chalky kernels[2]	3.0	7.0	6.0
Glutinous kernels	1.0	1.5	1.5
Unhusked grains (paddy), number of grains in 1 kg	5	13	5

[1] See Table 2 for explanations

[2] Opaque, chalky area extends over half or more of the milled rice grain

Source: adapted from TMOC 2016a, b, c

(Se) and dietary fibre, amylose content as related to starch digestibility, and harmful presence of arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg). Protein content of the rice grain is controlled largely by environmental factors, especially N supply in the soil (Eggum and Juliano 1975; Perez et al. 1996), and is generally associated negatively with grain yield. Nevertheless, some rice varieties with higher protein contents than others grown in the same environment and at similar level of grain yield have been identified (e.g. De Datta et al. 1972; Juliano 1993). Although breeding lines of high protein rice have also been developed, the extremely low heritability of protein content has proved to be a constraint (Coffman and Juliano 1987). In contrast to the wheat protein content which plays a crucial role in market and price differentiation (e.g. see Bale and Ryan 1977; Espinosa and Goodwin 1991), rice protein is generally unrecognised by the market and consumers.

Habitual preferences for rice with certain quality features sometimes prevent the nutritional value of rice from being fully utilised. The inverse relationship between rice amylose content and the glycemic index, which measures how carbohydrate in a food rapidly raises the blood glucose, has long been established (Juliano and Goddard 1986). However, the benefit can only be realised when people suffering from type 2 diabetes are convinced to change their eating habits to rice with lower glycemic index, e.g. from soft textured rice cooked from low amylose varieties to firmer textured rice cooked from varieties with higher amylose, or from glutinous to non-glutinous rice. Brown rice is considered nutritionally superior to white rice on the account of its higher content of dietary fibre, vitamins, minerals, essential fatty acids and beneficial phytochemicals (Slavin et al. 1999; Liu 2002). Most rice consumers object to its coarse texture when cooked, as well as variability in the cooking condition due to the presence of the pericarp, with higher price being another deterrent. The cost of storage and transportation of brown rice is substantially increased by the need to stabilise lipids, which are located mainly in the aleurone cells and embryo and removed as bran in milling (Juliano 1993), against rancidity which would otherwise quickly develop as the result of oxidation and hydrolysis (Champagne et al. 1991). For example, brown rice which accounts for less than 1% of Thailand's rice export in the mid-2010s was priced 40% higher than white rice for the highest grade non-aromatic rice and 17% higher in the case of Hom Mali (computed from data in TREA 2019).

Numerous local rice varieties and landraces have been identified with a higher Fe and Zn concentration than widely grown mega-varieties (e.g. Pintasen et al. 2007; Anandan et al. 2011; Saenchai et al. 2012; Jaksomsak et al. 2015; Jamjod et al. 2017), but benefits from these are largely local and limited to those who grow the rice for their own consumption and others who depend on the same source of rice. Wider use is constrained by a negative association between grain nutrient contents and yield, as shown in the case of Zn (Jaksomsak et al. 2017). The high Zn trait in some modern rice genotypes, on the other hand, was shown to be yield independent and stable over a wide range of available Zn in the soil, with a number identified as Zn biofortified breeding lines (Wissuwa et al. 2008). However, the inverse association between yield and grain Zn density was demonstrated with IR68144, one of the Zn biofortified breeding lines, and a Thai mega-variety CNT1, when grown together at the same location IR68144 produced brown and white rice with more than 150% of the Zn concentration but only 60% of the grain yield of CNT1 (Phattarakul et al. 2012).

The un-husked rice seed can be loaded with more than 100 mg Zn kg^{-1} by timely foliar Zn application, but only about a quarter of this reaches inside the husk (Boonchuay et al. 2013). Nevertheless, foliar Zn application during the early stage of grain formation has been shown to be most effective in increasing the Zn content of brown and white rice (Phattarakul et al. 2012), and equally effective when the Zn was applied together in the same spray as a pesticide or fungicide (Ram et al. 2016). Different genetic engineering approaches to increase Fe concentration in the rice endosperm continue to be proposed (e.g. Goto et al. 1999; Zimmermann and Hurrell 2002; Trijatmiko et al. 2016; Wu et al. 2019), but research and development are often hindered and slowed down by consumer and policy resistance activism against genetically modified crops (Paarlberg 2002). The Fe and Zn concentration of rice varieties considered low in these nutrients, while unaffected by parboiling, can be easily raised by adding salts such as $FeSO_4$ and $ZnSO_4$ to the paddy while it is soaked prior to steaming (Prom-u-thai et al. 2010a, b, 2011a, b). Selenium (Se) is another essential micronutrient that accumulates in rice in a lower concentration than in other staple crops, with negative health impacts on an estimated one billion people globally (Combs Jr 2001, also cited by Carey et al. 2012; Boldrin et al. 2013). Selenium concentration in brown rice in Spain was found to be closely associated with total and available Se in the soil (Rodrigo et al. 2017). Unlike Zn, the Se in rice was more responsive to soil application than foliar Se (Boldrin et al. 2013).

The presence of As, Cd, Pb and Hg is a cause for concern in rice, which is consumed in much larger amounts than other foods by many people for their whole life. Arsenic is a naturally occurring problem exacerbated by wetland rice cultivation, when the As in the groundwater brought up to irrigate rice is concentrated in the soil by evaporation, and leached back down the soil profile by the rain and flood water to elevate the groundwater As further. In Bangladesh, where excessive levels of As have been found in deep tube wells used for irrigation and shallow wells for drinking and other domestic uses, As content of the rice grain was found to be unaffected by the soil As, which had a negative impact on grain yield (Panaullah et al. 2009). Compared with the safe standard for rice at 1 mg As kg^{-1}, a large survey found 0.23 ± 0.12 mg As kg^{-1} in farmers' rice grain in South-western Bangladesh (Rahman et al. 2010), and as much of the As is allocated to the husk and bran fraction of the grain (Rahman et al. 2007) even lower concentration of As is expected in white rice. Critically high levels of heavy metals were found in rice grown in soils affected by industrial pollution in China (e.g. Fu et al. 2008; Hang et al. 2009; Zhao et al. 2010), although the levels of Cd, Pb and Hg in milled rice in the retail market throughout Zhejiang province of China were found to be below the maximum allowable concentration (Huang et al. 2013). The problem of environmental contamination, however, can cause serious problems where rice is consumed in the same location where it is grown, as happened to people living immediately downstream from a zinc mine in Thailand, who were found eating rice with toxic levels of Cd that they grew themselves (Simmons et al. 2003, 2005; Sriprachote et al. 2012).

Phosphorus (P) and zinc (Zn) are two nutrients that have been reported to have adverse effects on early growth and establishment of rice when their concentration in the seed is too low. Rice seed with higher P concentration, raised by applying P to the soil on which the mother plants were grown, produced seedlings with better shoot growth when grown aerobically on a low P soil (Ros et al. 1997). However, applying P directly on the seed had varying effects depending on the P compound used and how it was applied (Ros et al. 2000). Treating the rice seed with phosphate salts prior to sowing increased shoot growth, although germination was delayed for 2–3 days with rock phosphate coating, and more than halved by coating with soluble phosphate salts, while soaking the seed in phosphate solution depressed germination with little effect on shoot growth. Rice seedlings also grew better with the seed that had been enriched with Zn, by foliar Zn application to the mother plants (Boonchuay et al. 2013) or soaked in a weak (2.5 mM) solution of $ZnSO_4$ (Prom-u-thai et al. 2012). Applying Zn powder to the rice seed before sowing resulted in more rapid germination and seedlings with better shoot and root growth (Slaton et al. 2001). Rice genotypes with exceptionally high seed Zn, as found in local varieties grown in the highlands of northern Thailand, are expected to be better adapted to the slash and burn cultivation in which Zn deficiency in the soil is exacerbated by increased alkalinity with the ash from burning (Jaksomsak et al. 2015).

The local impacts of rice with nutrient enrichment or contamination are obvious. The production of nutrient-enriched rice, by means of rice genotypes that accumulate more of the nutrients in their endosperm or by strategic fertilisation, will directly benefit those farming households who consume the grain or plant the seed grown by themselves, and others in the community who depend on the same source of rice. However, while the cost of sorting and keeping separate rice with higher prices are passed on to consumers, the same price incentive cannot be expected to operate in keeping the nutrient-enriched rice from the non-enriched grain for delivery to the low-income target population who live further away, i.e. the urban poor. Following the success at the farm, with rice grown from nutrient-enriched varieties or agronomic biofortification, a practical means for differentiating the grain nutrient contents will be essential in the paddy market, along with a mechanism for establishment and maintenance of a segregated channel for the nutrient-enriched rice in the value chain, specifically targeting low-income rice consumers. The golden rice, on the other hand, could be highly marketable as a premium quality and priced rice for its high beta carotene content and remarkable colour, along the same line as pigmented rice in black, purple or red colour (e.g. see Htwe et al. 2010a, b; Panomjan et al. 2016; Pusadee et al. 2019), although this would be contrary to the objective of its development in overcoming vitamin A deficiency in low-income rice consumers.

6 Conclusion

Rice quality improvement is seen as a means to increase return to farmers, in addition to yield gains. The eco-geographical condition, especially in the production of rice in the highest price ranges, makes upgrading to the highest price unrealistic as an objective of quality improvement. Within each of the many different types of rice produced and consumed throughout the world, price increases as the result of improvement in quality have been achieved through breeding and management. Resistance to milling breakage exemplifies a quality feature that contributes to quality improvement and price increase for every type of rice due to near universal preference for the rice kernels that are largely unbroken, with a concrete example in the impact of combine harvesting in conjunction with mechanical paddy drying and parboiling. Essential to rice quality management are the sorting of the paddy from Asia's numerous small farms, with a diverse range of ecological and socio-economic conditions, and postharvest management that differentiate among rice of different grain types and quality. This process of quality control is crucial in rice quality improvement, as farmers, traders and mills are rewarded for better quality with higher prices. In the absence of sorting and quality control, in contrast, rice of inferior quality is produced when heterogeneous shipments of paddy are bulked and milled together; efforts in quality improvement are wasted. Nutrient enrichment of the rice grain, another aspect of quality improvement achievable through breeding and agronomic management at the farm, cannot be translated into increased intake of the nutrient in low-income rice consumers without a mechanism to distinguish the enriched grain and keep it segregated from the non-enriched grain. Similarly, the cost of enriching parboiled rice with Fe and Zn can hardly be expected to be borne by consumers with low income. It is essential for the implementation of ambitious rice development strategies aiming to increase the value of rice by improving grain quality to recognise that (a) there are eco-geographical limits in the production of rice in the highest price ranges, (b) post-harvest management is essential for maintaining and sometimes enhancing the quality achieved at the farm, and (c) quality differentiating mechanism is required to segregate rice of different grades and prices, and also nutrient-enriched rice targeting low-income consumers from non-enriched grain.

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Compliance with ethical standards

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