Malaysian Applied Biology
https://doi.org/10.55230/mabjournal.v54i2.3187

Review Article

Global and Malaysian Aromatic Rice: A Comparative Review on The Quality, Production, and Breeding Spectra

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ABSTRACT

Aromatic rice is a premium rice variety due to multiple distinctive essential qualities *viz*., strong aroma, long grain, intermediate amylose content, and intermediate gelatinization temperature. The strong aroma is majorly contributed by 2-acetyl-1-pyrroline (2AP), a volatile organic compound that is 10-100% higher in aromatic rice. The long grain represents a large endosperm that contains more starch and nutrients. Intermediate amylose content in aromatic rice is preferred as the rice becomes moist and tender upon cooking. As for the gelatinization temperature (GT), aromatic rice has an intermediate GT which defines a shorter time in cooking. In the world, major aromatic rice cultivars include Basmati (India & Pakistan) and Khao Dawk Mali 105 (Thailand). The production of the aforementioned varieties as well as other minorities is declining due to multiple constraints. The demand-export clash, climate change, disease outbreaks, and other abiotic factors have proven challenging for all rice industrial players. Several breeding techniques are practiced in combatting those problems. In the past, conventional pure line breeding had proven to initiate the cultivation of Basmati-370 (India) and Khao Dawk Mali 105 (Thailand). However, hybrid breeding (combination of desirable traits) is a much more effective breeding method through the release of Pusa Basmati-1 (India), Lateefy (Pakistan), and MRQ104 (Malaysia). From the genetic perspective, quantitative traits locus (QTL) mapping is used to assist in the breeding of aromatic rice cultivars. QTL mapping successfully improved yield, agronomic traits, and stress resistance by providing a strong foundation for advanced in-depth breeding technologies including marker-assisted selection (MAS), mutagenesis, and CRISPR/Cas9 mediated genome editing.

Key words: Aromatic rice, breeding strategies, essential quality, global, Malaysia, production trends

INTRODUCTION

Rice (*Oryza sativa* L.) is the main staple food worldwide, supplying over 20% of the daily calories needed by the human population (Food & Agriculture Organization, 2022). The production cum consumption of rice in the world is constantly tough, accelerated by both economic and population growth especially in most Asian and African nations (FAO, 2022). The inverse proportionality of demands to production was also faced by the powerhouse of rice exporters, India. According to the United States Department of Agriculture (USDA, 2023), India's 2021/2022 consumption increased by almost 1.5 million tonnes, 7% higher than the year earlier. The conflict between local demands and exports had been widely discussed as both were important. Hence, the stakeholders of rice industries are constantly competing in developing new rice varieties with three main focuses: high yield, resistance to multiple diseases as well as better tolerance towards environmental stresses (Fahad *et al*., 2019).

The economic values of rice are widely influenced by two main classes: non-aromatic rice and aromatic rice. Aromatic rice is more premium and unique due to its subtle aroma, flavor, and texture (Roy *et al*., 2020; Singh *et al*., 2000; Dwiningsih & Alkahtani, 2022a). However, most development programs do not emphasize the improvement of aroma and grain quality as they are much more worried about the local demands clash rather than complex issues such as aroma (Verma *et al*., 2018; Sharma & Khanna, 2019). The higher cost of aromatic rice cultivation, limited cultivation area, and small diversity of varieties led to a premium price standardization within the global market (Kaewmungkun *et al*., 2023). These giant producers of aromatic

Article History
Accepted: 12 May 2025
First version online: 30 June 2025
Cite This Article:
Akmal Shukri, A.I., Abdullah, S., Abdullah, N.S., Hussein, S., Abdul Aziz, N., Ab Razak, M.S.F., Ahmad, F., Hasan, N.A. 2025. Global and malaysian aromatic rice: A comparative review on the quality, production, and breeding spectra. Malaysian Applied Biology, 54(2): 1-18. https://doi.org/10.55230/mabjournal.v54i2.3187

rice could only focus on exporting as it brought much return on investment (ROI). A list of notable aromatic rice in the world is tabulated in Table 1.

Table 1. List of notable aromatic rice varieties in the world and Malaysia

Country of origin	Variety	Common characteristics	References
India	Basmati, Gandhakasala, Jeerakasala, Mushk Budji, Pusa Basmati, Tulaipanji	Long slender grain, very strong aroma	Verma *et al*. (2018)
Thailand	Jasmine / Khao Dawk Mali 105	Medium to long grain, strong aroma (jasmine flower-like / *Pandan*-like)	Roy *et al*. (2020)
Pakistan	Basmati 370, Basmati 385, Basmati 515, Pakistan Basmati, Super Basmati	Long slender grain, very strong aroma	Akhter & Haider (2020)
Vietnam	ST25, Nang Thom Cho Dao, Nep Cai Hoa Vang, Seng Cu, Tam Thom	Medium to long grain, strong aroma (flower-like)	Khanh *et al*. (2021)
Indonesia	Rojolele, Batang Gadis, Bengawan Tunggal, Pandanwangi, Sintanur	Short grain, short days to maturity, strong aroma (*Pandan*-like)	Sholehah *et al*. (2020); Dwiningsih & Alkahtani (2022a)
Bangladesh	BRRI dhan50, BRRI dhan37, BRRI dhan38, BRRI dhan70, BRRI dhan80	Long slender grain, strong aroma	Hossain *et al*. (2021); Vemireddy *et al*., (2021)
Iran	Anbar-boo, Domsiah, Hassan, Hassani, Mehr, Mirza, Mosa Tarom, Sadri, Salari, Saraie, Tarom	Medium to long grain, strong aroma	Verma *et al*. (2018)
Afghanistan	Bara, Bala, Lawangi, Pashadi-Konar, Sela Doshi, Sela Takhar, Surkhabala, Surkhamabain	Long slender grain, strong aroma	Sarhadi *et al*. (2015)
Japan	Jakou, Hakamuri, Kabashiko, Miyakaori, Touboshi	Medium grain, strong aroma	Okoshi *et al*. (2015)
United States of America	Della, Kasmati, Texmati	Medium to long grain, moderate aroma, low yield	Lalitha & Vinayan (2020), Singh *et al*. (2000)
Malaysia	MRQ 50, MRQ 74, MRQ 76, MRQ 88. MRQ 103, MRQ 104	Medium grain, moderate aroma	Ariff *et al*. (2019); Ramli (2019); Ramli *et al*., (2021); Rahman *et al*. (2020)

Over the years, various factors have severely hindered the operations of major aromatic rice producers (Fahad *et al*., 2019). In general, aromatic rice is becoming lower in yield rate, susceptible to various diseases and lodging intolerance despite the large production (Mahajan *et al*., 2018; Roy *et al*., 2020). A major notable factor in these problems is global climate change. The aroma and kernel elongation of aromatic rice are best developed when the cultivars are grown in cooler areas such as Uttar Pradesh in India, Kashmir in Pakistan, and the northern part of Thailand (Roy *et al*., 2020; Verma *et al*., 2022). Whenever the global climate shifts and the temperature rises, the endosperm would not be optimally efficient in producing the volatile compound responsible for the aroma, e.g. 2-acetyl-1-pyrroline (2AP) (Prodhan & Qingyao, 2020). The period to reach maturity will increase gradually as the biochemical pathway of those cultivars is affected. Discussing diseases, and prolonged time to reach maturity will only make the diseases worse. In Malaysia for instance, no local aromatic varieties were identified as resistant to bacterial leaf blight (BLB) disease (Ramli, 2019). The long monsoon season brings a lot of rain hence encouraging the growth of the responsible pathovar, *Xanthomonas oryzae* pv *oryzae* (Ramalingam *et al*., 2020). It is then up to the choice of breeding techniques which could produce better aromatic rice with higher yield, premium agronomic traits, wider spectrum of disease resistance as well as superior cooking and eating quality.

Different countries have distinct measures of aromatic rice breeding. Common techniques include pure line breeding, hybridization of varieties along with transformation and regeneration of agronomic essential genes (Patra & Chakraborti 2020; Varatharajan *et al*., 2021; Hassan *et al*., 2022). Before the emergence of marker-assisted selection (MAS), researchers and breeders ultimately depended on pure line breeding method to produce better progenies including Jeerakasala (Kerala, India) of 1966 and Pakistan Basmati (Kala Shah Kaku, Pakistan) of 1968 (Singh *et al*., 2000). However, pure line breeding has limited potential as the environment is quickly evolving hence reducing the survival rate of these pure varieties. Hybridization is a much better choice as it provides flexible combinations of preferred traits, wide adaptability to the environment, better grain quality, and higher resistance to diseases (Mahajan *et al*., 2017). One famous hybrid aromatic rice is Basmati Hybrid-1 which produced around 6001 – 7500 kg/ha at early cultivation, higher than pure line varieties such as Basmati itself and CB11 (Singh *et al*., 2000). Biotechnological advancements also bring extensive success towards aromatic rice breeding via marker-assisted selections which provide the benchmark for existing genes and quantitative local traits (QTLs) analysis (Verma *et al*., 2018; Vemireddy *et al*., 2021). These techniques helped in locating and targeting specific genes for the transformation and regeneration of preferred agronomic traits including salinity tolerance, lodging tolerance, disease resistance, and many more (Viana *et al*., 2019; Hossain *et al*., 2021). More recent technologies for improving aromatic rice include the use of clustered regularly interspaced palindromic repeats (CRISPR/Cas9) and the induction of mutagenesis through chemical and physical mutagens (Viana *et al*., 2019; Ashokkumar *et al*., 2021; Tang *et al*., 2021).

This study reviewed the relationship between the quality & production of aromatic rice globally and in Malaysia, along with comprehensive breeding strategies to cope with demands and consumption. The review moved along past or present data which was then concluded with a concrete set of recommendations for global and Malaysian rice industrial players including breeders, researchers, and farmers.

Aromatic rice of the world

Essential quality of aromatic rice

The essential quality of aromatic rice can be classified into two important categories: grain quality and cooking quality. The quality is preferred globally as it brings special values for consumers *viz*., exquisite aroma, longer sizes, better nutritional content, faster cooking process as well as higher economic returns (Singh *et al*., 2019). The particular traits of aromatic rice are illustrated in Table 2 which distinguished them from the other rice groups.

Table 2. Particular traits of aromatic rice

Trait	Scale[1]		A particular trait of aromatic rice	Example
Grain length	The distance from the base of the lowermost sterile lemma to the tip (apiculus) of the fertile lemma/palea. The length is taken in a mean value of 10 grains.		The majority of aromatic rice = long and slender grains. Few have similar or shorter grain lengths than the non-aromatic groups ([2])	Long grain = Basmati (India), Super Basmati (Pakistan) ([2, 10])
	Less than 3 mm Short			Short grain = Indonesian varieties (Batang Gadis, Rojolele) ([7])
	3 – 5 mm Medium			
	5 – 7 mm Long			
Decorticated grain: aroma	1 2 3	Absent / very weak Weak Strong	3 = Strong ([3-6])	All aromatic rice cultivars ([3-6])
The amylose content of the grain	Less than 5%	Very low	Low to intermediate amylose content ([7-8])	Low amylose content = Khao Dawk Mali 105 ([11])
	5-20%	Low		
	20-24.9%	Intermediate		
	25-30%	High		Intermediate amylose content = Jeerakasala, Tulaipanji (India) & Basmati 370, Pakistan Basmati (Pakistan) ([2,10])
	More than 30%	Very high		
Alkali digestion (as an indication of gelatinization temperature)	Alkali digestion	Gelatinization temperature	Low to intermediate gelatinization temperature ([9])	Low = Khao Dawk Mali 105 (Thailand) ([11])
	Low	High (75-79°C)		
	Intermediate	Intermediate (70-74°C)		
	High	Low (55-69°C)		Intermediate = Basmati (India), Pusa Basmati 1121 (Pakistan) ([2,10])

Source: [1] [International Rice Research Institute (IRRI), 2013], [2] (Yadav *et al*., 2023), [3] (Ashokkumar *et al*., 2020), [4] (Chan-In *et al*., 2020), [5] (Hu *et al*., 2020), [6] (Luo *et al*., 2022), [7] (Dwiningsih & Alkahtani, 2022a), [8] (Sharma *et al*., 2023), [9] (Verma *et al*., 2018), [10] (Singh *et al*., 2000), [11] (Vanavichit *et al*., 2018)

Grain quality

Fragrance or aroma has been considered one of the most highly valued grain quality traits in rice (Verma *et al*., 2018). Western consumers often describe this fragrance as the resemblance of popcorn or roasted nuts (Mahajan *et al*., 2017). Meanwhile, the Orientals equate the aroma to pandan leaves (*Pandanus* sp.) or jasmine flowers (*Jasminum* sp.) (Beltran *et al*., 2021; Wei *et al*., 2021). In East Africa, aroma is the primary factor for purchasing rice in their market (Ndikuryayo *et al*., 2022). Various research revealed the presence of natural chemicals / volatile compounds that contributed to the exquisite aroma (Ashokkumar *et al*., 2020; Chan-In *et al*., 2020; Hu *et al*., 2020; Luo *et al*., 2022). As of 2022, nearly 500 volatile compounds were identified in various aromatic and non-aromatic rice including alcohols, aldehydes, esters, furans, hydrocarbons, indoles, ketones, and a few minor compounds such as benzene rings and nitrogens (Lina & Min, 2022). Analytically, the major chemical related to aroma is 2-acetyl-1-pyrroline (2AP) as found in major aromatic rice cultivars including Basmati and Jasmine (Singh *et al*., 2019; Behera & Panda, 2023). The concentration of 2AP differs during the growth period of rice. A high concentration of 2AP is initially detected in leaves during the early stage and booting stage (maximum) while decreasing at the reproductive stage (Kongchum *et al*., 2022; Ndikuryayo *et al*., 2022). The decline of 2AP concentration in leaves happens as it is transported and accumulates grains during later stages (Hinge *et al*., 2016; Ndikuryayo *et al*., 2022). The non-aromatic rice also possesses 2AP, but 10–100 times lower than that of the aromatic variety (Wakte *et al*., 2017). Several notable aromatic compounds include indole (Goolarah and KDML 105 varieties), 2-phenylethanol (Basmati variety) as well as 2-tredicanone (japonica aromatic varieties) (Singh *et al*., 2000; Zhao *et al*., 2022; Chen *et al*., 2023). On the genetic overview, the initial report came from Ahn *et al*. (1992) through the identification of a single-copy marker, RG-28 on chromosome 8, which is closely linked to the scent gene (*fgr*1). Analytically, the intensity of aroma is measured at the ripening stage through the vaporization of the main aromatic component in rice, the 2-acetyl-1-pyrroline (IRRI, 2013; Prodhan & Qingyao, 2020). In recent times, the development of an E-nose (Electronic nose) system has been proven to assist in measuring the volatile aromatic compounds (VOC) responsible for aroma in rice (Xu *et al*., 2021). Generally, the E-nose is more reliable, rapid, and accurate than the conventional method responsible for measuring aroma intensities (Xu *et al*., 2021).

Long grain is another special trait of aromatic rice. As tabulated in Table 1 based on IRRI (2013), grain length can be classified as short (less than 3 mm), medium (3–5 mm), and long (5-7 mm). According to Singh *et al*. (2000) and Yadav *et al*. (2023), the most premium aromatic rice groups (Basmati, Pusa Basmati & Jasmine) have medium to long grains and could elongate more during the cooking process. Meanwhile, several modern aromatic rice varieties such as Indonesian's Batang Gadis or Rojolele have similar grain lengths (short) to non-aromatic varieties (Dwiningsih & Alkahtani, 2022a). Akin to aroma, kernel/grain elongation is also influenced both by genetic factors and the environment, especially temperature at the time of ripening (Singh *et al*., 2000; Punia & Kumar, 2022). South and Southeast Asians mutually preferred rice with long grains (Khush & Juliano, 1985; Butardo *et al*., 2019). Based on a report by Custodio *et al*. (2019), long grain is a premium quality of rice as acknowledged by rice industry stakeholders and farmers from six countries *viz*., Thailand, The Philippines, Vietnam, Cambodia, India and Bangladesh. Generally, the length of grain is largely influenced by geographical and climate factors. In the Punjab region of India, Basmati elongates more than in Sindh, Pakistan due to the lower temperature in Punjab (Singh *et al*., 2000). Multiple reports have quoted the maximum elongation in grains matured at cooler temperatures (~25°C in the daytime, ~21°C during the night) (Singh *et al*., 2000; Mahajan *et al*., 2009; Singh *et al*., 2019). In addition, longer grains contain larger endosperms which potentially carry more starches and other nutrition compounds (Li *et al*., 2018). For instance, Jasmine is classified as a long-grain aromatic variety (Taratima *et al*., 2019), while Basmati falls into the extra-long grain class (Kesh & Khan, 2023). Another dominant name is Pusa Basmati 1121 which has a kernel length of 8.2 mm, one of the highest among aromatic rice cultivars (Jaiswal *et al*., 2015). Moreover, grain length is positively associated with grain weight. As stated by Li *et al*. (2018), the yield of rice is largely determined by three main traits: the number of panicles per plant, the number of grains per panicle, and grain weight. A breeding program that enhances the importance of grain length will eventually affect the grain weight and yield increment as a whole. In countries with low yields of aromatic rice such as China and Malaysia, the focus on grain length improvement should be emphasized to increase the values and quality of their own local aromatic cultivars.

Another key quality of aromatic rice is the optimal content of amylose. Amylose determines the hardness of cooked rice, the gloss of the final product, and the rice-water ratio (Custodio *et al*., 2019; Park *et al*., 2019). For example, waxy/glutinous rice will remain firm, and sticky and does not increase in volume due to the low content of amylose (Sultana *et al*., 2022). Most aromatic rice are moist, tender and do not become hard upon cooking as they have low to intermediate amylose content (Dwiningsih & Alkahtani, 2022a; Sharma *et al*., 2023). The preference for amylose content in rice is distinguished by geographical and local delicacy factors. South Asians prefer Basmati with an intermediate amylose amount (20 – 24.9%), while Southeast Asians prefer low-amylose varieties (5-20%) such as Jasmine (Custodio *et al*., 2019). In the past, pioneer Basmati cultivars including Basmati 370 and Pakistan Basmati have intermediate amylose content between 19-26%. Meanwhile for Khao Dawk Mali 105 of Thailand, reports recorded that the aromatic cultivar has low amylose content among other Asian aromatic cultivars (Vanavichit *et al*., 2018). Moreover, low amylose content is the reason for a stickier texture in Jasmine rice when cooked (Taratima *et al*., 2019). Analytically, several methods are practiced in measuring the amylose content of rice including differential scanning calorimetry (DSC), precipitation with carbohydrate-binding protein Concanavalin A (*Con*A), and spectroscopy (Kaufman *et al*., 2015; Custodio *et al*., 2019).

Cooking quality

Gelatinization temperature (GT) is an important trait measured to deduce the cooking quality of rice. According to Butardo *et al*. (2019), GT is described as the temperature of starch to begin melting upon cooking rice flour in a specific water ratio. GT is important to deduce the duration and energy needed to cook milled rice (Nikitha & Natarajan, 2020; Roychoudhury, 2020). Generally, the GT of rice are classified as low (55-69°C), intermediate (70-74°C) and high (75-79°C) (Juliano, 1972; Sharma & Khanna, 2019). From the perspective of the global market, aromatic rice is highly demanded due to its moderate degree of gelatinization which concluded less energy and time consumption for cooking (Verma *et al*., 2018). A high gelatinization temperature is not preferable as it becomes excessively soft upon cooking (Wang *et al*., 2020). KDML 105 / Jasmine (Thailand) has a low degree of gelatinization and soft gel consistency upon cooking (Mahajan *et al*., 2017, Vanavichit *et al*., 2018). Meanwhile, Basmati (India), Pusa Basmati 1121 (Pakistan), and Rojolele (Indonesia) have intermediate gelatinization temperatures with soft gel consistency (Mahajan *et al*., 2017). GT is also important in assisting the identification of Quantitative Traits Locus (QTL) of certain preferable thermo-sensitive genes in rice such as the Granule Bound Starch Synthase I (*GBSSI*) gene and Starch Synthase IIa (*SSIIa*) gene (Arikit *et al*., 2019; Verma *et al*., 2020). Multiple projects are identifying and enhancing the importance of GT-related genes to optimize the cooking quality of aromatic rice in Thailand and India (Singh *et al*., 2017; Arikit *et al*., 2019; Kaewmungkun *et al*., 2023).

The combination of essential quality in aromatic rice varieties

Consumers preferred rice with multiple combinations of strong aroma, light texture, and fluffy appearance upon cooking (Mahajan *et al*., 2017). As recorded, cooked aromatic rice has a light texture, is fluffier, and elongates better than non-aromatic varieties (Saeed *et al*., 2020). Basmati rice has an elongation ratio that nearly doubles upon cooking, with grains extending up to an additional 1.7 mm compared to other rice varieties (Mahajan *et al*., 2017). It becomes extra longer and fluffy with high-volume expansion of water. Besides that, Bahra of Afghanistan (Verma *et al*., 2018), Bashful of Bangladesh (Islam *et al*., 2018), and Domsiah of Iran (Cruz & Khush, 2000) also elongate almost 100% upon cooking. As in Southeast Asia, the superb cooking quality of KDML 105 (Thailand) is characterized by its strong aroma and soft texture. The polished grains are pearly, clear, very long, and slender, with a glossy exterior (Vanavichit *et al*., 2018). Rojolele from Indonesia also has a soft texture and elongates greatly upon cooking (Dwiningsih & Alkahtani, 2022a). As for aromatic D25-4 / Nga Kyee from Myanmar, it also elongates in double upon cooking, accompanied by a strong aroma (Golam & Prodhan, 2013). In the USA, Texmati is cultivated as a local aromatic substitute for Basmati (Bansal, 2021). However, it was lightly scented, had a strong flavor, and slightly less fluffy appearance than Basmati. The exceptional traits of cooked aromatic rice bring additional and special value to local delicacies. Basmati, Pusa Basmati, and Jeerakasala are known for making pulao and biriyani, famous traditional cuisines largely found in Bangladesh, India, Pakistan, and multiple parts of the Middle East (Bhattacharjee *et al*., 2002; Singh & Kumar, 2022). Since long ago, people from the aforementioned countries have resided in the USA, Canada, and major cities of European countries. As a result, they brought out the importance and need for their delicacies hence the increasing demands for local aromatic rice cultivation. Texmati, Sierra, and Neches are among the local aromatic rice cultivated in the USA to cope with these increasing demands of delicacies (Mahajan *et al*., 2017).

In Southeast Asia, consumers are highly dependent on fragrant rice imported from Thailand (Khao Dawk Mali 105 / Jasmine). When cooked, the rice retains its moist and soft texture which clings together yet sturdy (BERNAS, 2023). This rice variety is well known for its delectable taste and pandan-like aroma. They are best for Chinese-inspired dishes or steamed white rice. In Singapore, Jasmine rice is preferred for Hainanese chicken rice because the aroma is heightened greatly with the combination of certain herbs and spices. Meanwhile, in Thailand, steamed Jasmine rice is best to be paired with spicy Tom Yum or green curry (BERNAS, 2023). People on the north and east coasts of Malaysia prefer rice with a stickier texture as it is suitable for their local delicacies i.e., Nasi Dagang and Nasi Kerabu (Ramli *et al*., 2017). Glutinous rice (a type of sticky aromatic rice) is also preferrable by most Malaysians and Thailand citizens for their steamed 'pulut' delicacies, eaten with mango and coconut milk (Sulong *et al*., 2022). All in all, the original aroma, fluffy texture, and delectable taste of Jasmine rice do bring out the uniqueness in flavor combinations of the aforementioned dishes, which in the line increases the eating and economic quality of related parties.

Major producers of rice & aromatic rice

Rice was the third most-produced crop in 2020 (756.744 million tonnes), contributing to 9% of the world's exported crops after wheat and maize (FAO, 2022). During that year, 676.61 million tonnes or 89.41% of global rice production came from Asia alone. In 2020, the top three producing nations include China (213.611 million tonnes), India (178.305 million tonnes) and Bangladesh (54.906 tonnes) (FAO, 2022). The aforementioned countries plus five others from Asian continent (Indonesia, The Philippines, Vietnam, Thailand & Myanmar) also own 89% of the global rice cultivation areas (FAO, 2022). The vast cultivation areas in developing countries are due to the traditional demand for rice as a main source of nutrients and economic returns.

Currently, no comprehensive record exists detailing the total global production of aromatic rice. Current data primarily focuses on the major trade shares of aromatic rice varieties. The principal producers include India and Pakistan for the Basmati variety, and Thailand for the Jasmine variety (Behera & Panda, 2023). These aromatic rice prime exporters contributed around 12-13% share in the global trade of rice (Mahajan *et al*., 2017). These small proportions defined the reason behind the standardization of global premium prices as they are highly demanded but only produced in specific nations due to agroclimatic factors, economic influences, technology advancements, and human resources.

Production of aromatic rice in India

In India, the total production of rice for 2020 is 178.31 million tonnes (FAO, 2022). According to the annual plan, the government allocates 90% of its rice for local consumption, and the remaining 10% for export purposes (Palanisami *et al*., 2019). However, the actual proportion for consumption or export is way lower than the annual plan. Out of the projected 17.81 million tonnes for export in 2020, only 6.9 million tonnes of non-aromatic rice and 3.5 million tonnes of aromatic rice (basmati & its derivatives) were exported successfully (Central Rice Research Institute, 2013; Palanisami *et al*., 2019). Aromatic rice is majorly cultivated in the northern region of India including Punjab, Haryana, and Uttar Pradesh (Palanisami *et al*., 2019). In Punjab, the predominant varieties belong to the Basmati family *viz*., Basmati 217, Basmati 370, Basmati 385, Basmati 386, Punjab Basmati and Super Basmati (Mahajan *et al*., 2018). Pusa Basmati 1 and Taraori Basmati are cultivated in Haryana, meanwhile Jeerakasala (known as biriyani rice) is cultivated in Uttar Pradesh (Singh *et al*., 2000; Shannon *et al*., 2021). In Southern India, Gandhakasala and Jeerakasala are the only fine aromatic rice varieties grown there as they brought high grain yields of 2743 and 2179 kg/ha respectively (Blakeney *et al*., 2020; Sindhumole *et al*., 2023). Despite the good performances in aromatic rice production, India is facing serious problems regarding environmental threats (Patel *et al*., 2020). More than 50% area for aromatic rice in India is threatened by the fragile rice ecosystem (Mahajan *et al*., 2017). In India's northern part such as Punjab, the problems include submergence and drought at seedling stages, pest attacks (brown planthopper & stem borer), disease infections (bacterial leaf blight, brown spot & sheath blight) as well as soil salinity and weeds (Palanisami *et al*., 2019). Meanwhile, in Uttar Pradesh, they face problematic soils, erratic rainfall, waterlogging, and floods in rice cultivation areas (Palanisami *et al*., 2019). Additionally, labor shortages in Punjab and poor adaptation of crop technology in Uttar Pradesh are other constraints that lead to a decline in production. The shortage in supply to a decline in export quantity.

Production of aromatic rice in Pakistan

In Pakistan, the annual rice production comprises 70% coarse types and 30% basmati (fine) types (Akhter & Haider, 2020). In the 2017-2018 crop season, 3.5 million hectares of granary areas were used for basmati cultivation, which was 6% higher than the previous season (Akhter & Haider, 2020). Before the establishment of the proper aromatic rice research station in Kala Shah Kaku, twenty-seven (27) basmati rice varieties have been released and commercialized for local and global consumption (Nader *et al*., 2019). Basmati 370 (1933) has been used as the mother variety of almost all local varieties including Pakistan Basmati (1968) and Super Basmati (1996) (Nader *et al*., 2019; Behera & Panda, 2023). Punjab is Pakistan's sole region of basmati cultivation due to its suitable agro-climatic and soil conditions (Jabran *et al*., 2019). Back in 2016, the export value of Pakistan's rice was 24.2 billion USD with 480 million USD accounted for basmati-type rice (Javed *et al*., 2020). Although the export values are huge among other producers except India, Pakistan's rice exports have declined at an annual rate of -4.1% from 2011 to 2015 (Javed *et al*., 2020). This insignificant trend is largely caused by socio-economic or environmental factors. From the socio-economic view, production is halted due to a lack of the latest technological knowledge, high labor costs, absence of credit and financial aids, unstable market prices, and lack of information on market penetration (Ebram *et al*., 2021). As for environmental threads, Pakistan basmati cultivars are greatly affected by diseases such as bacterial leaf blight (BLB) disease (Arshad *et al*., 2020), brown leaf spot disease (Aslam *et al*., 2021), and bakanae disease (Sarwar *et al*., 2018). Despite the increase in granary areas for basmati cultivars until 2019, the recorded average yield is significantly low (10-40% less than the previous 5 years) due to the emergence of the aforementioned disease especially BLB (Akhter & Haider, 2020).

Production of aromatic rice in Thailand

Thailand is the world's sixth main producer and third main exporter of rice in 2020 (FAO, 2022). In Thailand, milled rice products are differentiated into four main classes based on price and market namely white rice, glutinous rice, parboiled rice, and Thai aromatic rice (Rerkasem, 2017). As for aromatic rice, Thailand is the main producer cum exporter of Khao Dawk Mali 105 (KDML 105), commercially known as Jasmine rice (Singh *et al*., 2000; Verma *et al*., 2018). 70% of the rice area in Thailand is occupied with KDML 105 together with its mutagenized compeer, RD15, and RD6 (Jongdee *et al*., 2006; Vanavichit *et al*., 2017). In records, Thung Kula Rong Hai / TKRH (the northeastern part of Thailand), is the main area for Jasmine rice cultivation (Jirapornvaree *et al*., 2021). TKRH is a common name given by the local authorities to acknowledge the regions of Buri Ram, Si Sa Ket, and Surin which are responsible for producing high-quality Jasmine rice (Yongcharoenchai, 2016). Annually, 9.4 million tons of Thai Jasmine rice were produced from 4.3 million hectares of rice areas in the aforementioned regions (Varinruk, 2017; Vanavichit *et al*., 2018). Among other milled rice products, Jasmine rice has the most premium quality which leads to high demand and prices (Rerkasem, 2017). Despite the large production and export values of Jasmine rice, Thailand is facing continuous constraints regarding environmental and socio-economic influences. From the environmental perspective, Jasmine rice is at risk of declining due to vigorous climate shift (Amnuaylojaroen *et al*., 2021; Jirapornvaree *et al*., 2021), soil organic carbon segregation (Arunrat *et al*., 2018) and changes in rainfall intensity (Boonwichai *et al*., 2018). These environmental constraints led to an increase in management and maintenance costs via the cost of fertilizers, irrigation, pesticides or even processing cum storage. As for socio-economic influence, the production is affected by less accessibility to infrastructures and current technology (Limnirankul *et al*., 2015), low buying prices by middlemen from farmers (Yongcharoenchai, 2016), and tight competition with Jasmine-alike varieties such as Tham Thom from Vietnam & Phka Rumduol from Cambodia (Thong *et al*., 2020; Khanh *et al*., 2021).

Aromatic rice of malaysia

History and cultivation of aromatic rice in Malaysia

Malaysia is a country that relies greatly on rice import activity. Back in 2020, Malaysia only managed to reach a 73.4% self-sufficiency level (SSL) for rice, hence needed to import around 26.6% to cope with local demands (Ministry of Agriculture & Food Industry, 2021). Malaysia imports around 200,000 metric tons of rice annually with values exceeding 1 billion USD (Ramli et al., 2021). Among the total numbers, 30% are fragrant varieties from Thailand (Jasmine), India (Basmati), and Pakistan (Pusa Basmati) (Jamal et al., 2014; Ramli et al., 2021).

Malaysian aromatic rice is developed under the Malaysian Specialty Rice Development Program (Rahman et al., 2020). Since the early 90s, this program has focused on the development of new local rice varieties with Basmati or Jasmine-alike traits including good grain elongation ratio, strong aroma, and soft texture upon cooking (Rahman et al., 2020; Sunian et al., 2022). Until today, 12 special varieties have been released by the Malaysian Agricultural Research and Development Institute (MARDI) including glutinous rice varieties (Pulut Malaysia 1, Pulut Siding, Pulut Hitam 9 & Masria), brown rice varieties (MRM 16 & MARDI Warna 98), as well as aromatic rice varieties (MRQ50, MRQ74, MRQ76, MARDI Wangi 88, MRQ103 & MRQ104) (Rahman et al., 2020; Ramli et al., 2021; Sunian et al., 2022).

Characteristics and production of Malaysian aromatic rice

Six aromatic rice varieties were developed and commercialized by MARDI between 1999 – 2022 (Table 3). Generally, all varieties were developed through a hybrid crossing technique with either both or one parental variety originating from the aromatic groups. As observed in Table 3, these varieties need between 113 and 125 days to reach maturity. According to Zainuddin et al. (2011) and Sunian et al. (2019), the maturity period is higher compared to all Malaysian non-aromatic varieties such as MR297 (110-115 days) and MR219 (105-111 days). As for yield rate, the values cannot be classified into high or low (IRRI, 2013) due to multiple factors including seed viability, environment adaptability, plant maintenance as well as biotic/abiotic threats control (Fahad et al., 2019). The jurisdiction of yield rate could only be compared between varieties or the contribution percentages toward total production. As of 2023, the highest yield rate among Malaysian aromatic rice varieties was illustrated by MRQ88 and MRQ74 at 63% and 55.79% respectively (Sunian et al., 2019; Ramli et al., 2021). Even at 63%, the percentages are classified as low when compared to the average yield rate of Malaysian non-aromatic rice varieties at 68% - 75% (Sunian et al., 2019; Ramli et al., 2021). Yield is the most complex character of rice as it can be affected by other agronomic trait performances, as well as multiple biotic or abiotic factors (Fahad et al., 2019). Early maturity and high yield are two main targets for the rice industry in the Malaysian National Agrofood Policy 2021-2030 (MAFI, 2021). Consequently, MARDI and other related institutions are focusing more on the non-aromatic varieties due to better quality and return for the nations.

Table 3. Characteristics of the six most prominent local aromatic rice varieties

Characteristics	MRQ50	MRQ74 (Mas Wangi)	MRQ76	MRQ88	MRQ103 (MARIA)	MRQ104
Released year	1999	2005	2011	2016	2022	2022
Parents	Q34 (DP) x KDML (RP)	Q34 (DP) x (Kasturi x KDML) (RP)	Q72 (DP) x Cuicak Wangi (RP)	IR 831 (DP) x MRQ74 (RP)	MRQ 89 (DP) x MRQ 50 (RP)	MRQ50 (DP) x MRQ89 (RP)
Breeding method	Hybrid crossing	Hybrid crossing	Hybrid crossing	Hybrid crossing	Hybrid crossing	Hybrid crossing
Days to maturity (days)	123 days	125 days	113 – 117 days	125 days	117 – 120 days	115 – 122 days
Average yield percentage (%)	ND	55.79%	43.75%	63.00%	50.31%	49.30%
Yield potential per hectare (t/ha)	4.5 t/ha	5.5 t/ha	3.4 – 6.2 t/ha	4.5 – 5.0 t/ha	> 5.0 t/ha	3.0 – 5.4 t/ha
Amylose content	ND	23.4%	17.0%	Intermediate	25.4%	23.5%
Glycemic index	ND	62 (moderate)	90 (high)	ND	51 (low)	51 (low)
References	Golam & Prodhan (2013); Engku *et al*. (2019); Abdullah *et al*. (2020); Elixon *et al*. (2022); Razak *et al*. (2020)	Jamal *et al*. (2014); Engku *et al*. (2019); Abdullah *et al*. (2020); Razak *et al*. (2020); Elixon *et al*. (2022); Ramli *et al*. (2023)	Abdullah *et al*. (2020); Ramli *et al*. (2021); Elixon *et al*. (2022)	Engku *et al*. (2019); Elixon *et al*. (2022); MARDI (2023)	Ramli *et al*. (2023)	Ramli *et al*. (2021)

ND = No Data

In addition, the production of Malaysian aromatic rice is not enough for local consumption or export purposes. The production is largely influenced by environmental factors in Malaysia including climate change (warmer than most aromatic rice cultivation areas in Pakistan and India), outbreak of major diseases (bacterial leaf blight & tungro disease) as well as water supply (irrigation, drought & flood) (Rajamoorthy & Munusamy, 2015; Firdaus et al., 2020). Moreover, the production was halted and still in re-trial for multiple locations due to the emergence of bacterial leaf blight disease that occurred in various local granary areas including Padang Besar, Perlis and Sungai Besar, Selangor (Jonit et al., 2016; Chukwu et al., 2019). On the positive side, the production of certain Malaysian aromatic rice such as MRQ 103 and MRQ 104 still continued for health purposes. Both MRQ 103 and MRQ 104 have a low glycaemic index (GI) which is suitable for the diet of diabetic patients (Hamid, 2021; Ramli et al., 2021; Radio Televisyen Malaysia, 2022). Despite the challenges, the development of aromatic rice must still be emphasized as it brings outstanding quality as discussed thoroughly in the previous subtopic (the essential quality of aromatic rice).

Breeding strategies for aromatic rice

Different ecosystems of rice demanded every nation to progress with multiple breeding strategies via conventional or modern breeding methods (Figure 1). As quoted by Rohmawati et al. (2021), there should be a proper balance between yield and enhancement of seed quality in every aromatic rice breeding program. Conventional breeding methods were proven to be reliable for decades before the adoption of prevalent, advanced, and innovative breeding techniques. Despite multiple breeding techniques, long-term solutions viz., hybrid breeding, marker-assisted selection (MAS), introgression of preferred genes, or mutation breeding were preferred and applied to develop aromatic varieties with higher yield, favorable agronomic properties, and longer survival rates in any ecosystem (Verma et al., 2018; Niones et al., 2019; Dwiningsih & Alkahtani, 2022b).

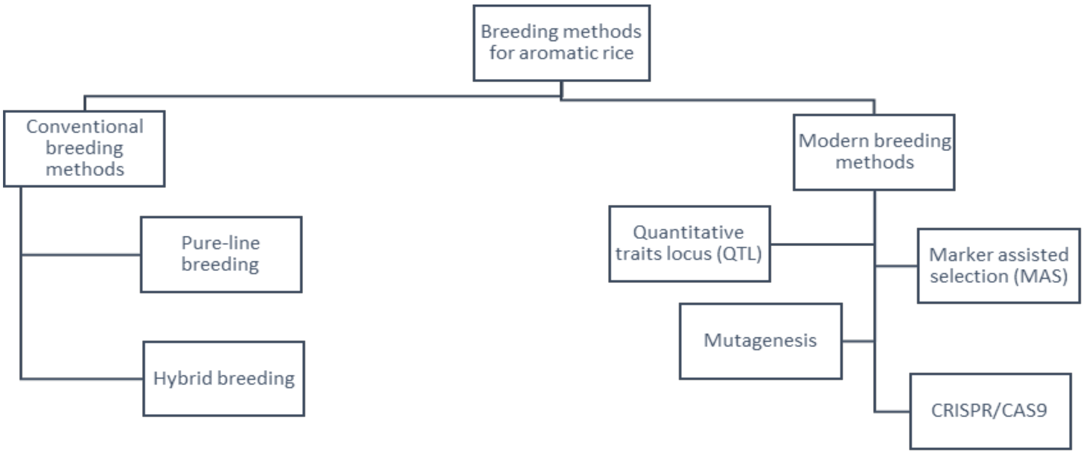

Fig. 1. Breeding methods for aromatic rice

Conventional breeding methods

Pure-line selection

The pure-line selection was applied to improve the locally adapted landraces while purifying and maintaining their advantageous features (Singh *et al*., 2000). Pure-line selection implies three basic steps to allow the evolution of local varieties: selection of individuals from a local variety or mixed population, phenotypic evaluation of individual progeny, and comparative yield trials (Rathore & Ram, 2013; Nakwilai *et al*., 2020). The pioneer and most successful example of pure line selection is Basmati-370 at Kala Shah Kaku (previously in India, but now in Pakistan) (Akhter & Haider, 2020). Basmati-370 has become the benchmark/parent for the existence of high-quality Basmati derivatives such as Pusa Basmati 1121, Kashmir Basmati, and Ranbir Basmati (Kour *et al*., 2019; Nader *et al*., 2019). Each new variety was selected purely from the parental lines that show distinguished preferred traits such as higher yield, early maturity, and better grain quality (Singh *et al*., 2000; Salgotra, 2018; Samal *et al*., 2019). In Southeast Asia, some aromatic rice lines related to pure line selections are Khao Dawk Mali 105 (KDML 105) from Thailand and Nang Huong from Vietnam (Vanavichit *et al*., 2018; Palanisami *et al*., 2019). At the initial level of KDML 105 selection, several lines were collected from Chachoengsao (central province of Thailand) for observation and selection (Hossain *et al*., 2021; Vemireddy *et al*., 2021). As a result of pure line selection based on yield and yield-attributing traits, line no. 105 was selected for mass breeding and commercialization, giving rise to the name KDML 105. Pure line selection is also important for the redevelopment and breeding of former high-quality varieties. Generally, the yield and quality of aromatic rice are inversely proportional to time due to biotic and abiotic stresses. The breeding and commercialization of one variety could be stopped and replaced with a better variety. In the southern region of Bangladesh, the renowned local Balam variety (similar to Basmati) is set to be reintroduced through pure line selection or hybridization to maintain the local field diversity (Ahmed *et al*., 2015). As for Afghanistan, the study by Sarhadi *et al*. (2015) suggested that Afghan native rice cultivars such as Pashadi-Konar, Sela Doshi, Sela Takhar, Surkhabala and Surkhamabain could be used for further local breeding programs. Pure selections of Afghan native lines are needed to filter the best lines that suit the current environmental conditions for yield optimization. Unlike Asia, the USA has a different ecosystem of rice which limits the cultivation of Basmati-like varieties (USDA, 2023). As a solution, they adapted the pure line selection in California (warm dry summers, with mild winters) through the cultivation of Della, Delrose, Delmont, and Sierra, which have a slightly similar long grain and strong aroma of Basmati (after cooked) (Mahajan *et al*., 2017).

Hybrid breeding

Hybrid breeding is undeniably the most common conventional method for aromatic rice development (Aljumaili *et al*., 2018; Verma *et al*., 2018). Pedigree selection, backcross, and pseudo-backcross improvements are examples of hybrid breeding methods that increase the conventional breeding speed and enhance the pyramiding process through a reduction number of breeding generations (Singh *et al*, 2000; Haque *et al*., 2021). Hybrid breeding is often used to combine preferred traits such as high yield, strong aroma, disease resistance, and salt tolerance from two different parental cultivars (Fahad *et al*., 2019). The most notable varieties resulting from the hybrid approach are Pusa Basmati-1 and Pusa Basmati 1121. Pusa Basmati-1 was the first ever dwarf, photosensitive, input responsive high yielding variety invented through hybrid breeding (Singh *et al*., 2000; Hossain *et al*., 2021; Vemireddy *et al*., 2021). Notable in its ancestry are the Basmati 370 and Karnal local for aroma and grain quality characteristics, while TKM6, IR8, Ratna, and IR72 for yield and resistance (Singh *et al*., 2000).

In Malaysia, hybrid breeding has been applied by MARDI to develop all local aromatic rice varieties (Rahman *et al*., 2020; Ramli *et al*., 2021; Shukor, 2021). For example, in 2022, MRQ104 was commercialized for its higher yield and low glycemic index properties (Rahman *et al*., 2020; Ramli *et al*., 2021; Shukor, 2021). This variety resulted from a cross between MRQ89 and MRQ50 upon pedigree selection (Ramli *et al*., 2021). Tracing the pedigree, both parent varieties are the descendants of Kasturi (India) and KDML (Thailand) which brought the long grain and strong aroma properties (Ramli *et al*., 2021).

Modern breeding methods

Modern breeding methods can be defined as the application of modern, advanced, and in-depth technology to produce new high-quality crops; either by assisting in current conventional breeding methods or specific personal breeding paths. The combination of conventional breeding with molecular approaches has increased the success rate of producing new progenies with desirable traits (Verma et al., 2018; Viana et al., 2019). Several advanced breeding methods include quantitative traits locus (QTL) mapping, marker-assisted selection (MAS), mutation breeding, and genome editing (Chukwu et al., 2019; Viana et al., 2019; Hossain et al., 2021). With the assimilation of precise rice genome sequences and stable conventional techniques, many candidate genes for diverse traits have been cloned and characterized (Mishra et al., 2018; Sabar et al., 2019; Vemireddy et al., 2021).

Quantitative Traits Locus (QTL)

Quantitative traits locus (QTL) mapping allows the genomic regions of responsible traits to be located in the chromosome (Verma *et al*., 2018). Generally, it allows the identification of current or novel genes related to the phenotypic appearance in plants (Viana *et al*., 2019). QTL mapping has been very helpful in the development of aroma and other agronomic traits in current and new varieties (Haque *et al*., 2021; Ndikuryayo *et al*., 2022; Behera & Panda, 2023). Besides that, the efficient and accurate mechanism of QTL mapping has allowed novel QTLs to be discovered continuously until today. The earliest QTL related to fragrance, *for* gene was identified in 1992 on chromosome 8 through the restricted fragment length polymorphism (RFLP) marker, RG28 (Ahn *et al*., 1992; Singh *et al*., 2000; Roy *et al*., 2020). Right after the discovery of high-density linkage maps in 2004, the underlying gene (*fgr*) on chromosome 8 was discovered to encode the betaine aldehyde dehydrogenase (BADH) enzyme (Bradbury *et al*., 2005; Gaur *et al*., 2016). Recently, five novel QTLs related to yield and agronomic traits were identified in a cross between Sonasal and Pusa Basmati 1121 cultivars (Malik *et al*., 2023). As for drought tolerance property, the most significant QTL is *qaro8.1*, located on chromosome 8 (Ndikuryayo *et al*., 2022). Besides mapping of yield and agronomic traits-related QTLs, the foundation of QTLs related to biotic stresses and cooking quality are also emphasized in aromatic rice. For example, the mapping of blast resistance gene in Burundi local rice cultivar has led to the improvement of their local aromatic variety, Supa 234 (Prodhan & Qingyao, 2020; Ndikuryayo *et al*., 2022). Many discoveries and introgression of disease tolerance QTLs are done for Pusa Basmati derivatives. Previous and current research include Bakanae tolerance QTLs in recombinant inbred lines (RILs) of the Pusa Basmati 1342 cultivar (Fiyaz *et al*., 2016), blast and sheath blight tolerance QTL in Pusa 6B cultivar (Singh *et al*., 2015), and BLB tolerance in Pusa Basmati 1509 (Sagar *et al*., 2020). In Thailand, KDML 105 was introgressed with multiple disease tolerance genes through the discovery of QTLs related to blast disease tolerance (Korinsak *et al*., 2022) and brown spot disease tolerance (Songkumarn *et al*., 2019). Besides that, the mapping of KDML105 is done to identify QTLs related to photosensitivity trait, starch gelatinization, and salt tolerance (Vanavichit *et al*., 2018). On the aspect of cooking quality, the discovery of grain elongation QTLs in Basmati (India) and Pathum Thani (Thailand) by Arikit *et al*. (2019) could be a catalyst factor for further improvement of rice line with good elongation ratio upon cooking. All in all, the foundation of multiple QTLs for aromatic rice had set a stable database and resources for breeding programs through marker-assisted selection (MAS), mutation breeding, and mediated genome editing.

Marker-assisted selection (MAS)

Marker-assisted selection (MAS) is a smart and fast breeding technique utilized in plant breeding development programs (Henkrar & Udupa, 2020). The usage of molecular markers in MAS enabled easy detection of polymorphism in rice crops, as well as the presence of desirable and resistant genes (Chukwu *et al*., 2019). Several types of markers are used in MAS of rice crops *viz*., restriction fragment length polymorphism (RFLP) markers, random amplification of polymorphic DNA (RAPD) markers, amplified fragment length polymorphism (AFLP) markers, single nucleotide polymorphism (SNP) markers and simple sequence repeat (SSR) markers (IAEA, 2002; Nadeem *et al*., 2020; Amiteye, 2021). However, the most common marker used for the MAS of aromatic rice is the SSR marker. Some advantages of SSR markers include co-dominance, high genomic abundance, high reproducibility, hyper-variability, increased reliability in detection, as well as high efficiency in time, space, and cost (Yasmin *et al*., 2017; Spencer-Lopes *et al*., 2018; Chukwu *et al*., 2019). Basically, SSR markers were simply used for the identification and comparison of aromatic genes in various rice varieties (Rohmawati *et al*., 2020). At a much-advanced level, SSR markers act as jump starters for a successful MAS breeding program. SSR-MAS has been employed in aromatic rice breeding programs to improve agronomic trait(s) as well as tolerance levels against various stresses (Sagar *et al*., 2020; Arabzai & Gul, 2021; Salgotra *et al*., 2021; Dwiningsih & Alkahtani, 2022b; Korinsak *et al*., 2022). Vemireddy *et al*. (2021) also illustrated successful stories of the MAS technique through improvisation of aroma, disease resistance, introgression of dwarf trait, as well as tolerance towards salinity, submergence, and drought. As for MAS for dwarf trait, an unnamed semi-dwarf variety was successfully developed through a cross between CSR10 (donor of semi-dwarf *Sd1* gene) and aromatic Kalanamak variety (recipient) in India (Srivastava *et al*., 2019). Samal *et al*. (2019) also developed a short-statured Ranbir Basmati variety through introgression of the semi-dwarf gene, sd1, and blast resistance gene, *Pi9* from an improved Basmati rice variety, Pusa Basmati 1637 (PB 1637). Several bacterial leaf blight (BLB) resistant aromatic varieties have been released through the introduction of different *Xa* genes (Chukwu *et al*., 2019). Laha *et al*. (2017) also reported the development of 'Improved Basmati' rice lines by combining BLB resistance genes (*Xa*13 & *Xa*21), blast resistance gene (*Pi*54), and a major QTL *qSBR* 11-1 for sheath blight resistance. As for abiotic tolerance, Dhawan *et al*. (2021) successfully introgressed *qDTY*1.1 (drought tolerance gene) from Nagina 22 (India non-aromatic variety) into Pusa Basmati 1. In Thailand, HM80 (submergence tolerant) along with HM84 (salt & drought tolerance) are two successful products of a cross between KDML 105 with two different sets of donors, IR49830-7-1-2-2 and Abhaya + Rathu Heenati respectively (Siangliw *et al*., 2003; Vanavichit *et al*., 2018; Behera & Panda, 2023). As for HM84, the variety was also introgressed with brown planthopper resistance genes and blast resistance genes (*BphQ*12, *Bph*32, *Bph*3 & *BLQ*1) (Vanavichit *et al*., 2018). Meanwhile, in Pakistan, Sabar *et al*. (2019) successfully developed a cross between Super Basmati (water sensitive) and IR55419-04, a drought-tolerant non-aromatic variety. MAS is also practiced in Vietnam through introgression of the *fgr* gene and BLB resistance genes (*Xa*4, *Xa*5 & *Xa*7) in aromatic varieties AC15, BT7, HDT8, HT1, Nghi Huong, N46, and SH8 (Khanh *et al*., 2021). Concurrently, the introgression of aforementioned traits into aromatic varieties has led to the development of better varieties with higher yields. Other advanced breeding techniques for aromatic rice include mutagenesis and CRISPR/Cas9-mediated genome editing (Viana *et al*., 2019; Hossain *et al*., 2021).

Mutagenesis

Mutagenesis is a process that changes an organism's DNA hence resulting in a gene mutation (Durland & Ahmadian-Moghadam, 2021). According to Viana *et al*. (2019), the heritable changes or mutations eventually result in new traits that are passed on from parent to offspring thus driving new evolution. One example is the discovery of higher 2-acetyl-1-pyrroline (2AP) content in gamma-irradiated Thai upland rice (Sansenya *et al*., 2017). The findings also indicated that the irradiated cultivars have stronger aroma due to indirect effects on the metabolic pathways of other aromatic volatile compounds including 1-hexanol, hexadecanoic acid, and nonanoic acid (Sansenya *et al*., 2017). Meanwhile in Indonesia, continuous research on the famous Rojolele variety was conducted by mutagenesis. Gamma irradiation and sodium azide (chemical mutagens) are commonly used to improve yield and tolerance against drought in Indonesia (Herwibawa *et al*., 2019; Dwiningsih & Alkahtani, 2022a). In 2020, the Centre for Isotope and Radiation Application, National Nuclear Energy Agency (CIRA-NNEA) of Indonesia successfully developed a semi-dwarf, early matured Rojolele variety through gamma-irradiated seeds (Dewi *et al*., 2020). In addition, another Indonesian aromatic "Pare Bau" variety was also exposed to heavy-ion beam irradiation before being cultivated in Tana Toraja, South Sulawesi, Indonesia (Okasa *et al*., 2021). As a result, 13 out of 18 cultivated M_3 lines have a higher yield than their parental cultivar (unirradiated Pare Bau). All lines also have high heritability values (h_2b) which conclude higher percentages of trait inheritance into the next generations including high-yielding properties (Okasa *et al*., 2021). Meanwhile, in Vietnam, 10 out of 20 local aromatic varieties had improved agronomic traits as well as higher zinc and iron contents after gamma treatment (Khanh *et al*., 2021). In Malaysia, mutagenesis is widely used for the research and development of non-aromatic rice varieties. In 1984, the first Malaysian gamma-induced rice variety was commercialized and known as Tongkat Ali (Ahmad *et al*., 2020). Tongkat Ali rice variety was named similarly to a Malaysian local herb due to the strong culm which can withstand strong wind during heavy rain seasons (lodging tolerant) (Ahmad *et al*., 2020). In 2015, NMR151 and NMR152 were registered in the FAO/IAEA Mutant Variety Database (MVD) as the pioneer mutant rice varieties from Malaysia (FAO/IAEA, 2024). Both varieties are successful examples of gamma induction on commercial MR219 seeds (Hussein *et al*., 2020). The varieties have a yield rate of 40-67% higher than the current varieties and are resistant to certain diseases such as leaf blasts, panicle blasts, and bacterial leaf blight (BLB) disease (Hasan *et al*., 2020; Hussein *et al*., 2020).

CRISPR/Cas9

CRISPR/Cas9 or clustered regularly interspaced palindromic repeats is a gene-editing technology that corrects errors in the genome as well as switching genes on or off quickly and with ease (Redman *et al*., 2016). This gene-editing mechanism consists of two main components: a guide RNA (to match a desired target gene), and Cas9 (CRISPR-associated protein 9)—an endonuclease that causes double-stranded DNA to break, hence allowing genome modifications (Haque *et al*., 2021). CRISPR/Cas9 is still a new technique in rice genome editing especially for aromatic cultivars. In terms of aroma, CRISPR/Cas9 changed the revolution of aromatic rice through the editing of OsBADH2 gene, skipping *OsBADH*$_2$ axon 2, creation of novel alleles of *OsBADH*$_2$ and multiplex gene editing Cyt-450 and *OsBADH*$_2$ gene (Imran *et al*., 2023). Tang *et al*. (2021) demonstrated the facilitation of exon-skipping induction in an aromatic rice variety using the CRISPR/Cas9 method. The study provides the first evidence that CRISPR/Cas9 can induce exon skipping of *OsBADH*$_2$ by mediating the deletion of exonic nucleotides (Tang *et al*., 2021). Later in 2021, Ashokkumar *et al*. (2021) successfully utilized CRISPR/Cas9 technology to enhance 2AP levels through the creation of novel alleles of the *OsBADH*$_2$ gene. In addition, CRISPR/Cas9 editing also assisted in the increment of grain size and grain cell numbers besides enhanced aroma in the IR-96 variety (Usman *et al*., 2020). In Vietnam, CRISPR/Cas9 was successfully applied to design the gRNA sequence in the BC15 variety, by editing the *OsPP5CS* gene that is accountable for salt and drought tolerance (Phuong & Hoi, 2017; Khanh *et al*., 2021). Other recent developments in aromatic rice cultivars through CRISPR/Cas9 editing include BLB resistance Mentik Wangi cultivar (Indonesia) (Rifhani *et al*., 2023), glutinous and aromatic Huiliangyou 858 cultivar (China) (Zhang *et al*., 2023) and salt tolerant Lianjing 11 (China) (Jingfang *et al*., 2023).

Progressive recommendation for malaysian aromatic rice

Generally, climate condition is a major influence on optimal aromatic rice production. Cooler areas such as Uttar Pradesh (India), Kashmir (Pakistan), and Tarai (Nepal) have a high productivity rate of aromatic rice (Verma et al., 2018). Classified as a tropical climate nation, Malaysia faces a hot and humid climate throughout the year. For example, the dry and hot climate led to a decline in rice production in the major rice cultivation area of Sekinchan, Selangor (Hazim & Yap, 2024) as well as in Kota Bharu, Kelantan (Astro Awani, 2024). As in Sekinchan, the production decreased from 11 tonnes per hectare (1st harvest season of 2023) to just 5 tonnes per hectare (2nd harvest season of 2023) due to the increasing temperature and absence of rainfall (Hazim & Yap, 2024). Meanwhile, in Kelantan, the projected rate of rice production for 2024 is expected to decline by up to 30% due to the impact of increasing temperatures and extreme drought conditions on the water level of the Kemubu River, the main source for rice fields (Astro Awani, 2024). To sum it all up, a production loss of RM21.6 million (2017-2021) was recorded due to the extreme drought seasons across Malaysia (Sinar Harian, 2021). As a solution, the optimization of cool climate areas could be a catalyst to enhance the production rate. Malaysia could be well aware of high-altitude agriculture areas including Cameron Highlands (Pahang), Tawau, Kundasang, and Tenom of Sabah; as well as Kelabit or Bario Highlands (Sarawak). Multiple local rice varieties are believed to be cultivated on a small scale across Sabah and Sarawak for local consumption only. The introduction of one or two dominant aromatic varieties in these areas could enhance the production for Malaysia as a whole. Agricultural investors and major rice companies could play some roles through the investment for new cultivation areas, capital for small farmers to initiate mass cultivation of dominant aromatic varieties, and agricultural inputs for plant maintenance. Besides that, the government should intervene in providing sufficient resources for the cultivation, promotion, and commercialization of more than 30 local aromatic rice from Sabah and Sarawak (Aljumaili et al., 2018). An efficient system should be conducted to optimize the yield as well as explore the potential of new areas for these varieties. If the system is good, the employment rate and life quality will also increase eventually.

Another problem for the Malaysian rice industry is the obsolete direct irrigation system, which should be optimized for aromatic rice production. A good irrigation system should provide sufficient supply when needed, as well as eliminate excessive levels when it should. In Malaysia, repeated irrigation problems happened at Kedah and Perlis under the responsibility of MADA (Muda Agricultural Development Authority). Two main problems for the system are slow rate and one-way path of water distribution (Mutalib, 2023). Slow distribution of water could lead to a decline in yield due to insufficient supply for growth at the right time. As for the distribution path, most MADA rice fields did not have different inlets and outlets of water. Hence, it is difficult for farmers to eliminate the excessive water during floods which eventually lead to plant death. On a positive note, Malaysia should learn from India and Pakistan that maximize the optimization of water for basmati rice through adjustment of transplanting time (Matloob et al., 2022). They delayed the transplanting of some basmati cultivars resulting in higher water productivity from reduced irrigation requirements. Another optimization of water supply is the alternate wetting and drying system or AWD. This system has been applied by Thailand farmers, in which the rice fields are only flooded intermittently rather than most of the growing seasons (Suwanmaneepong et al., 2023). AWD can reduce water use in rice by up to 30% compared to traditional continuous flooding methods. On the side of environmental quality, AWD could also reduce methane emissions by up to 30-70%. (Suwanmaneepong et al., 2023). An underground water system could also provide more water to rice fields especially in the drought / dry season even if it is much more costly than other methods. According to Tatar et al. (2020), the creation and maintenance of pure water potential in the soil is important to minimize drought stress during plant development stages. All in all, new and effective irrigation should be applied to ensure the consistent quality of Malaysian aromatic rice, as well as minimize the risks of water imbalance during drought or flood seasons.

As for rice yield and stress management, the application of most recent technologies should be applied in the Malaysian rice research industry. Malaysia loses around RM1.6 billion annually as we have to import more rice (Mutalib, 2023) due to the inefficiencies of conventional breeding including time-consuming, large expenses, laborious and tedious (Khan et al., 2014; Chukwu et al., 2019). Moving over time, the application of CRISPR/Cas9 mediated genome editing and mutagenesis could be the new stepping stones for the local aromatic rice development, especially in the aroma, grain elongation, and disease resistance properties (Hossain et al., 2021). However, cost and time could be the wall between success and failure. Rice industrial players should get aligned in collaboration and multiple ventures for aromatic rice development programs. For instance, the collaboration between Malaysian government bodies for rice industries (DOA, MARDI, BERNAS) with local and international research institutions could provide the necessary technologies in return for research outputs. As discussed earlier, conventional breeding techniques based on phenotypic analysis viz., hybrid breeding and conventional crossing are no longer effective for longer terms. On the aspect of disease resistance, introgression of the resistant gene(s) through marker-assisted selection (MAS) could be the most successful method (as elaborated in the previous subtopic under MAS of modern breeding methods). Furthermore, research institutions should prioritize developing new rice varieties that address the high demand both globally and in Malaysia. As denoted previously, Malaysia only reached 74% of the self-sustainability level for rice production, hence increasing the high percentages of imported rice from major powerhouses (MAFI, 2021). Instead of developing new varieties with additional cosmetic traits, it would be more beneficial to develop varieties that address and solve the persistent issues faced by consumers worldwide. As in Malaysia, MARDI is actively involved in addressing and solving major problems of the rice industry through the annual introduction of high-yield rice varieties, optimization of biopesticides and biofertilizers, as well as application of modernized milling and smart farming. However, there are still some long-term issues that need to be tackled accordingly by MARDI including the declining soil health and nutrient depletion, repetitive disease outbreaks such as BLB, and extreme weather events (e.g. flood and drought) that cause big losses among industrial players and farmers.

Lastly, the relationship gaps between farmers and rice industrial players should be solved. In most cases, the gaps originated from vague communications between the government, suppliers, and farmers regarding the supply of agricultural inputs (high price, insufficient amount, and late distribution (Ibrahim, 2024). In addition, the lack of knowledge and financial aid have widened the gap between farmers and higher parties in the rice production hierarchy. For example, the government did provide relevant financial schemes to enhance the local production rate including Skim Baja Padi Kerajaan Persekutuan, Skim Insentif Pengeluaran Padi, and Insentif Benih Padi Sah (Ibrahim, 2024). However, these are just some financial aids without proper guidance towards the sustainability of rice cultivation activity. In the first place, the government and related parties should provide enough information on the suitable techniques, varieties, and technologies for aromatic rice production first, before providing additional financial aid for them in the off-seasons and at the start of main seasons. As they are provided with sufficient information, they can plan the seasons well even if there are unforeseen circumstances regarding agricultural input supply. On an additional note, taking continuous feedback from the farmers and providing instant solutions is a good way to improve rice cultivation periodically. It could start with a continuous systematic survey that comprises their needs on rice breeding programs, the allocation of funds, quality of local rice fields, type and level of stresses on rice cultivars, as well as current cultivation technique(s). Moving from there, the rice research institutions together with the government and other industrial players could discuss providing the right assistance. Several programs should also be organized to elucidate the importance of aromatic rice to the nation. Rather than just inventing new varieties through theory and research approaches, getting feedback from the farmers is probably the best way to begin a new adventure and development.

CONCLUSION

In conclusion, aromatic rice has high-quality traits that should be enhanced and commercialized on a large scale. Besides the subtle aroma and taste, aromatic rice should be well-developed and cultivated for higher yield to solve the increasing demands of Malaysia and global as a whole. On a way to achieve that feat, the restriction imposed by multiple constraints *viz*., low yield, susceptibility to diseases and pests, as well as intolerance to abiotic stresses must be minimized or eliminated. Advanced breeding techniques such as marker-assisted breeding (MAS), mutagenesis, and CRISPR/CAS9 should be practiced thoroughly to replace the obsolete conventional breeding methods. Nonetheless, the conventional method could still be applied but with an improvement through the assistance initiated by the aforementioned modern techniques. The roles of every party in the rice industry are important too in ensuring a higher success rate. The relationship gap should be minimized to nurture a better culture in research, development, and commercialization. All in all, the key to a successful aromatic rice breeding program lies in the systematic management of technology, manpower, and relationships.

ACKNOWLEDGEMENTS

The authors would love to acknowledge the Ministry of Higher Education of Malaysia in awarding the grant for this research project: Fundamental Research Grant Scheme FRGS/1/2022/WAB04/UITM/02/3.

ETHICAL STATEMENT

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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