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REVIEW

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Effect of agronomic management on rice grain quality Part I: A review of Australian practices

Rachael Maree Wood[1,2] | Daniel L. E. Waters[1] | Andrew John Mawson[3] | Christopher L. Blanchard[1] | Brian W. Dunn[2] | Prakash Oli[2]

[1]Australian Research Council Industrial Transformation Training Centre for Functional Grains, Graham Centre for Agricultural Innovation, Charles Sturt University, Wagga Wagga, NSW, Australia

[2]NSW Department of Primary Industries, Yanco Agricultural Institute, Yanco, NSW, Australia

[3]The New Zealand Institute for Plant and Food Research Limited, Ruakura Research Centre, Hamilton, New Zealand

Correspondence
Rachael Maree Wood, ARC Industrial Transformation Training Centre for Functional Grains, Graham Centre for Agricultural Innovation, Charles Sturt University, Wagga Wagga, NSW, Australia.
Email: rachw512@gmail.com

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Abstract

Crop yield dominates rice (*Oryza sativa* L.) industry research; however, it is grain quality that dictates the value and market acceptance of rice. Key parameters of rice grain quality include physical appearance, amenability to processing and the cooking and sensory properties. In Australia, rice farmers who do not meet defined high-quality standards receive discounts to their payments. Consequently, even with high yields, poor grain quality can negatively impact grower returns. Despite the financial consequences, the quality of Australian grown rice is highly variable, because unfortunately, the underlying causes are poorly understood. The identification of genetic markers for specific traits largely dominates rice grain quality research, while research regarding the effect of crop management practices on grain quality is relatively sparse and generally lacks an Australian focus. Prior research that has assessed the effect of crop management practices on grain quality tends to focus primarily on milling quality and neglect the physicochemical and cooking properties. This review outlines the current state of knowledge of the role nutritional management, irrigation protocols, planting density, and the interaction with genotype and environment on rice grain quality. The review highlights the uniqueness of Australian management practices and that there is a need for future research to understand the impact of agronomic practices on rice grain quality in Australia. Understanding how each cultivar interacts with agronomic practices can help reduce the variability found within rice crops.

KEYWORDS

crop management, irrigation protocols, nutritional management, planting density, rice quality

1 | IMPORTANCE OF RICE GRAIN QUALITY TO THE AUSTRALIAN RICE INDUSTRY

Australian rice yields are the highest in the world at around 10 tonnes per hectare and of the grain produced, approximately 85% is exported (Department of Agriculture & Water Resources, 2018). Although producing high yields, Australia contributes a relatively small portion of global rice production and accounts for 0.1% of global rice trade (Workman, 2019). As Australia cannot compete in terms of quantity with other rice exporters, it remains competitive by producing high-quality grain targeted to premium markets (Lisle et al., 2000; Martin & Fitzgerald, 2002). Australian rice undergoes stringent quality testing before being traded as these niche markets have narrow specifications for each quality parameter (Lisle et al., 2000). For example, sushi rice exported into the Japanese market have strict protein concentration specifications with low protein grain (below 6.5% protein) attracting price premiums.

Head rice yield (HRY), the portion of grain that remains whole or at least 75% of the original length as a mass percentage of paddy, is an important grain quality parameter that influences the marketability of rice. In 2013, the Australian rice industry incurred more than $30 million in additional milling and product downgrade costs from low HRY (Lawson, 2014). To ensure growers continually produce high HRY grain, the Australian rice industry now issues penalties to producers who do not meet high HRY standards. Consequently, even with high yields, grower's returns are negatively impacted by poor grain quality. Despite these financial consequences, the HRY of Australian grown rice is highly variable, and unfortunately, the underlying causes are poorly understood.

Quality traits are dependent upon the particular end use and can vary according to local cuisine and culture. Unlike other cereals which are typically sold to the consumer as flour or another refined product, rice is consumed as intact whole milled grain, and thus, texture, flavor, and appearance cannot be compromised. The physical appearance of rice includes grain dimensions, HRY, grain color, and chalk. The presence of chalk, the opaque regions in the grain's endosperm, increases the likelihood of grain breakage during milling, thus reducing HRY. Factors such as amylose content, protein content, gelatinization temperature, and paste viscosity will affect the cooking and sensory properties of rice and differ between rice cultivars.

Milled rice is composed of starch (up to 95% dry weight), protein (5%–7%), and lipids (0.5%–1%) (Fitzgerald et al., 2009). Rice grains of high amylose (>25%) become firm and dry when cooked, whereas grains of intermediate (20%–25%)-to-low amylose content (12%–20%) have a softer and stickier texture (Juliano, 1979). Rice gelatinization temperature ranges from 55 to 85ºC, and grains with high gelatinization temperature will take longer to cook and have a harder cooked rice texture (Fitzgerald et al., 2009; Kealey & Clampett, 2005). Furthermore, a low gelatinization temperature (55–69.5ºC) is preferred over an intermediate temperature (70–74ºC) on all continents (Juliano & Villareal, 1993). Protein content and composition also contribute to rice texture with high levels of protein content associated with a hard and chewy cooked texture (Tamaki et al., 1989). Furthermore, the ratio of the different components of protein, albumin, globulin, glutelin, and prolamins impacts rice grain texture with high prolamin content being more closely associated with firmer cooked rice grains (Balindong, Ward, Liu, et al., 2018; Baxter et al., 2014).

Specific genes control many rice quality parameters (Fitzgerald et al., 2009), which breeding programs can utilize. However, growing environment also influences grain quality and the grain quality of advanced breeding lines must be tested in multienvironmental trials (MET). Despite environmental factors and grower management practices playing a significant role in influencing grain quality, research regarding the effect of crop management practices on grain quality is fragmented and generally lacks an Australian focus. Prior international research that has assessed the effect of crop management practices on grain quality tends to focus primarily on HRY and neglect the physicochemical and cooking properties. The lack of Australian grain quality research in the context of environment is in stark contrast with American rice research, one of Australia's main competitors for rice exports, which accounts for more than half of the research covered in this review. This review outlines the current state of knowledge of the role of crop management practices on rice grain quality and highlights the need for future research into Australian rice-growing practices.

2 | MANAGEMENT PRACTICES AFFECTING RICE GRAIN QUALITY

2.1 | Effect of nitrogen fertilizer management on grain quality

Nitrogen (N) fertilizer is an important farm management practice that not only improves yield but also impacts grain quality (Ning et al., 2009). By measuring the in-season plant N status, amylose and protein contents can be predicted (Ata-Ul-Karim et al., 2017). Several reports noted that increasing the N rate between 0 and 225 kg N/ha increases protein content, improves HRY, and decreases grain chalkiness (Ahmad et al., 2009; Ghosh et al., 2004; Grigg et al., 2016; Perez et al., 1996). The additional protein bodies through N application improve the structural integrity of the grain (Dilday, 1988; Grigg et al., 2016) by occupying the space between the loosely packed starch granules reducing cracks, grain breakage, and an opaque appearance improving HRY (Dilday, 1988; Grigg et al., 2016; Leesawatwong et al., 2005). Indeed, Balindong, Ward, Rose, et al. (2018) observed a higher protein content in unbroken grains compared with broken or incomplete grains.

Although increases in N rate generally improve grain strength during milling, extensive N rates increase grain protein content to such an extent it reduces milled grain appearance and cooking and eating quality (Champagne et al., 2007). Increasing N rate has been shown to decrease grain brightness and increase yellowness, reducing milled grain appearance (Kaur et al., 2016). Some prior reports (Ata-Ul-Karim et al., 2017; Gunaratne et al., 2011; Perez et al., 1996) suggest amylose content decreases as protein content increases while others have observed no significant interaction between protein content and amylose content (Champagne et al., 2007). However, Champagne et al. (2007) only examined two N rates, 122 and 224 kg N/

ha, and there was no control treatment (0N) whereas research that reported a decrease in amylose from increased protein content (Ata-Ul-Karim et al., 2017; Gunaratne et al., 2011; Perez et al., 1996) included treatments with multiple N rates between 0 and 370 kg N/ha. Furthermore, research that identified a negative correlation between protein content and amylose content analyzed *indica* cultivars while Champagne et al. (2007) analyzed cultivars with a *japonica* background and this may have contributed to the conflicting results.

Australian cultivars are mostly of the *japonica* type with some lines having some *indica* parentage (Kealey & Clampett, 2005). The N requirement of rice in Australia can sometimes exceed 224kg N/ha (Troldahl, 2018), the highest rate studied by Champagne et al. (2007). Ata-Ul-Karim et al. (2017) analyzed both rice subspecies using N rates up to 370 kg/ha and noted amylose content decreased as protein content increased in both *indica* and *japonica* cultivars. Thus, the amylose content of *japonica* cultivars could potentially be affected by high N rates and further Australian research is needed to examine amylose content at N rates above 224 kg/ha. Furthermore, the Australian rice cultivar with an *indica* percentage has a low glycemic index (GI) and a change to amylose content by high N rates could have negative consequences for its GI (Toutounji et al., 2019).

Increasing applied N also alters starch structure. Zhu et al. (2017) assessed *japonica* cultivars at 0, 150, and 300 kg N/ha in China and reported that starch granules became uneven and decreased in size with increasing N. These authors reported increased gelatinization enthalpy, starch swelling power, and solubility under high N rates while peak viscosity and gelatinization temperature decreased. Furthermore, Grigg et al. (2016) observed a decrease in final and peak viscosity from increased N up to 180 kg N/ha in long grain *japonica* cultivars in Arkansas. Gunaratne et al. (2011) investigated the effects of N, up to 231 kg N/ha, on *indica* rice flour in Sri Lanka and discovered swelling power and amylose leaching increased while peak viscosity and granular breakdown decreased. They attributed the change in cooking parameters to possible amylose and amylopectin structural changes due to increased protein content.

Although protein accounts for a smaller portion of the rice grain compared with starch (Fitzgerald et al., 2009), it can significantly affect cooked rice texture. Protein is negatively correlated with the stickiness of cooked rice, while hardness is positively correlated with protein content (Champagne et al., 2007). It is thought protein influences cooked rice texture by limiting the amount of water starch can absorb during the early stages of cooking (Martin & Fitzgerald, 2002). As protein content increases, from applied N, the overall Rapid Visco Analyser (RVA) viscosity curve decreases (Grigg et al., 2016; Gunaratne et al., 2011; Martin & Fitzgerald, 2002; Zhu et al., 2017).

N application can have differing effects on individual protein fractions (Ning et al., 2010). Albumin, prolamin, globulin, and glutelin are the proteins found in rice grain and are classified according to their solubility (Ning et al., 2009). Ning et al. (2010) demonstrated that in *japonica* cultivars grown in China, albumin and globulin were unaffected by N application, while prolamin and glutelin were significantly affected. Balindong, Ward, Rose, et al. (2018) reported that globulin and prolamin positively correlated with HRY, and thus, increases in HRY from N application may be related to increases in prolamin concentration.

Prior research has demonstrated that protein fractions have opposing effects on the textural properties of rice (Baxter et al., 2014). Specifically, the addition of albumin extracted from rice flour to rice starch increased the total amount of water uptake during cooking compared with pure starch, while prolamin, globulin, and glutelin had a lower total water absorption than pure starch. Altering the water absorption of rice starch alters its swelling ability which impacts cooked rice texture. Balindong, Ward, Liu, et al. (2018) demonstrated that prolamins and the prolamin: prolamin + glutelin ratio were more highly correlated with RVA parameters than amylose and total protein content in some sets of germplasm where amylose content differed by only 3%, whereas Baxter et al. (2014) reported that the effect on the pasting and textural properties was dependent upon the relative concentrations of all protein fractions. This research demonstrated the significant effect protein fractions have on rice quality and that the application of N can alter protein composition in *japonica* cultivars. Ning et al. (2010) reported that albumin and globulin were controlled by genetics, and thus, it is important to determine the impact of N on protein composition for Australian cultivars and how grain quality and end-use functionality might be affected. The impact of N application on protein fraction composition has not yet been published in Australia to date.

2.2 | The impact of application timing of nitrogen fertilizer

There is no appropriate soil nitrogen test for rice, so paddock history is used to estimate the appropriate basal nitrogen dose. N is the most limiting nutrient in rice production, and applying lower than required rates will affect crop growth and yield potential (Ata-Ul-Karim et al., 2017). Conversely, applying higher than required rates of N will cause excessive vegetative growth and lodging (falling over), resulting in yield losses through harvest complications. Plant recoveries of N fertilizer range from 48% to 68% when applied in a single basal application (Dunn et al., 2016). To reduce loses, the required N rate is often divided into multiple doses supplied at critical growth stages.

High N applied at the beginning of the season increases tillering and spikelet number per plant which is associated with reduced viable pollen per anther leading to an increase in sterile grain under low temperatures (Gunawardena et al., 2003). In south eastern Australia, the total N rate is often split into two applications to reduce the risk of cold temperature-induced sterility. The split N strategy involves applying two-thirds of the required N rate as the basal application and the remaining one-third at panicle initiation (PI).

While split N application increases crop yield (Dunn et al., 2016), data related to its impact on grain quality in Australia are limited. Perez et al. (1996) examined the effect of N application on grain quality using differing N rates applied before transplanting, at maximum tillering, PI, and flowering. They found that protein content, HRY, and translucency were higher with late (flowering) N application. However, in one season there was no difference in HRY between the control (0N) and the treatment where N application occurred before transplanting (100 kg N/ha) and at PI (50 kg N/ha; 150 kg of total N). Similarly, Dilday (1988) reported a significant decrease in HRY for both cultivars tested in the study when total N was split rather than applied as a single basal application. Perez et al. (1996) also noted that late N application had a greater effect on the grain protein content than the total N rate. Increased grain protein content improves the structural integrity of the grain increasing HRY; however, a reduction or no change in HRY by splitting N application found by both Dilday (1988) and Perez et al. (1996) indicates that factors other than total protein are influencing grain breakage during milling. It is interesting to note that protein content in the 150N treatment in Perez et al. (1996) study was ~1% higher than the control which is a large enough increase to elicit a change in cooked rice texture (Kaur et al., 2016).

Several researchers have demonstrated the timing of N application can have differing effects on individual protein fractions (Islam et al., 1996; Ning et al., 2010; Souza et al., 1999). Souza et al. (1999) reported that while albumin and globulin significantly increased when N was applied postflowering, prolamin was unaffected. Islam et al. (1996) found N application at flowering and 20 days postflowering had the greatest effect on glutelin and prolamin, respectively. Ning et al. (2010) noted that prolamin and glutelin contents were higher when a greater proportion of N was applied at PI (50:50) compared to an 80:20 split. Changes in protein composition may affect the cooking and sensory properties as the pasting and textural properties of rice are dependent upon the relative concentrations of all protein fractions (Baxter et al., 2014).

The synthesis of the different rice protein fractions occurs at different times during seed development (Yamagata et al., 1982). Yamagata et al. (1982) reported glutelin and globulin appeared five days after flowering, the prolamins appeared ten days after flowering, while albumin was synthesized consistently throughout seed development (Yamagata et al., 1982). Yamagata et al. (1982) noted that the development of the starchy endosperm of protein (PB) body type-II (glutelin and globulin) formed faster than PB type-I (prolamin). A change in grain protein composition may have caused the reduction in HRY found in the Dilday (1988) study, and as protein synthesis is a major sink for N application, it would be reasonable to conclude that the timing of N application may increase particular protein fractions while others may be unaffected.

Nitrogen application during grain development also impacts starch content and its composition. Increasing N fertilizer during grain development has been shown to decrease the total starch and amylose contents, but amylopectin remained unchanged (Xiong et al., 2008). Generally, as amylose decreases cooked rice firmness decreases (Fitzgerald et al., 2009), while stickiness increases (Juliano, 1979). Xiong et al. (2008) did not assess the effect of N application during grain development on processing and sensory quality but noted that taste could have been impacted due to a change in amylose and protein content.

N application in Australia either occurs as one dose at the beginning of the season or as the split method with the second dose at PI, differing from most rice-growing systems that apply multiple doses at critical growth stages. Prior research assessing the impact of split N on HRY has compared treatments with differing rates of total N or treatments differed in their basal N rate, making comparisons with the Australian system difficult. Within the same experiment in Perez et al. (1996), there were no single-dose treatments (applied as a basal dose) that were compared with a split treatment, applied before transplanting (basal) and at PI, that received the same total N rate. Therefore, changes in HRY could have occurred due to differences in total N rate rather than the additional N application at PI. In Dilday (1988), N was supplied at three and six different intervals during growth, and the initial N rate of the three-way split treatment was ~65–75 kg/ha lower than the single-dose treatment. Thus, the lower HRY in the split treatment could have occurred due to a reduced basal N rate compared with the single-dose treatment. Future research is needed to assess the effect of N application at PI on HRY and other quality parameters when the basal N rate or total N rate remains constant to determine whether differences are due to variations in total N or the additional N at PI.

2.3 | The impact of irrigation management on rice grain quality parameters

Drought and climate change projections have seen a reduction in the availability of water for irrigated rice production in south eastern Australia (Dunn & Gaydon, 2011). As a result, farmers are beginning to adopt water-saving techniques

(Dunn & Gaydon, 2011). Historically, aerial sowing, using pregerminated seed released from an aircraft to a flooded field, was the most popular sowing method for Australian rice growers. However, aerial sowing uses almost 15 Ml/ha compared with drill sowing, which can provide a 13% water saving. Hence, rice growers are now shifting from aerial to drill sowing (Dunn, 2018; Dunn et al., 2016).

Once seeds are drill sown, the field is intermittently irrigated until the introduction of permanent water (PW) to the crop occurring at around the 3–4 leaf stages. Delaying the addition of PW (delayed permanent water or DPW) until just before PI can provide an additional 19% reduction in water usage per hectare compared with conventional drill sown rice (Dunn, 2018). Removing PW postflowering and applying intermittent irrigation until maturity, known as delayed permanent water with post flower flushing (DPW + PFF), can potentially provide further water savings. A similar irrigation regime to DPW + PFF used in tropical climates is referred to as alternative wetting and drying (AWD). A period of flooding during the reproductive stage is required in southern Australia and other temperate climates to protect the crop from temperature fluctuations (Williams & Angus, 1994). DPW has proven to have no significant effects on grain yield (Dunn, 2018; Grigg et al., 2000); however, there is no research investigating the impact of DPW on rice grain quality in Australia, and globally research is limited.

Grigg et al. (2000) and Graham-Acquaah et al. (2019) reported that AWD did not affect HRY of rice grown in Arkansas, although these reports were from only one season and the grain physicochemical properties were not measured. A study conducted in Uruguay also found HRY of *indica* type cultivars was not affected by a water-saving technique similar to DPW; however, they did observe the effect was dependent on the growing region (Caracelas et al., 2019). In China, one study reported that AWD increased amylose content, protein content, and HRY but noted the response was cultivar dependent and quality decreased in some cultivars (Cheng et al., 2003). Increases in amylose and protein content have shown to increase cooked rice firmness. (Fitzgerald et al., 2009; Juliano, 1979; Tamaki et al., 1989). Cheng et al. (2003) observed an increase in both amylose and protein contents, and it would be reasonable to conclude grain grown using AWD would have a substantially higher cooked rice firmness compared with conventionally irrigated rice.

Graham-Acquaah et al. (2019) noted a significant increase in grain chalkiness in rice grown using AWD compared with drill sown rice with conventional irrigation; however, the change in chalkiness did not affect HRY. They reported a lower RVA setback viscosity in rice grown using AWD and attributed the difference in setback and grain chalkiness to a possible decrease in amylose content (Graham-Acquaah et al., 2019). Chalky grains are reported to have a lower setback viscosity and amylose content compared with translucent grains (Patindol & Wang, 2003). However, increased grain chalkiness and reduced amylose content can also occur due to high temperatures during the reproductive period (Yamakawa et al., 2007) and this may have explained the observed differences in Graham-Acquaah et al. (2019) study.

Intermittent irrigation during the vegetative stage causes a 12- to 16-day delay of pollen microspore compared with conventional irrigation (Dunn & Gaydon, 2011). Graham-Acquaah et al. (2019) sowed all treatments on the same day and applied a dry down cycle during the vegetative stage in the AWD treatment, and thus, there may have been a delay in pollen microspore. Grains in the AWD treatment could have experienced higher temperatures during the reproductive period compared with the continuously flooded treatment, affecting the results. When comparing grain quality between different irrigation treatments, sowing dates should differ to ensure that the reproductive periods of all treatments align to eliminate temperature as a factor.

Assessing the effect of DPW in Australia, Dunn et al. (2014) reported a higher nitrogen use efficiency of plants grown using DPW compared with that reported in prior Australian research which used conventional drill irrigation where PW was applied at the standard four-leaf stage (Becher et al., 1994; Dillon et al., 2012). Protein synthesis is a major sink for N, and thus, plants grown with DPW could potentially have a higher grain protein content than conventionally irrigated rice. Increased protein content would increase HRY but negatively affect cooked rice texture by increasing hardness and reducing stickiness (Champagne et al., 2007), factors which do not meet the preferences of Australian export markets, thus highlighting the need for research to evaluate the impact of DPW on grain quality in Australia.

Changes in water management will affect soil properties which are likely to affect nutrient solubility and hence nutrient availability to the plant (Rehman et al., 2012). One study indicated that the interaction between drought stress and zinc deficiency is likely due to a reduction in zinc transport toward the plant roots from reduced water availability (Gao et al., 2006). Furthermore, Gao et al. (2006), suggested that reduced water availability may also affect the movement of zinc within the plant. Indeed, Haldar and Mandal (1979) observed a decrease in the concentration of available zinc in soils with frequent water saturation, which is found when using AWD. DPW and DPW + PFF are management practices developed for temperate grown rice, and currently, there are limited data on its effect on the micronutrient concentration and availability in regards to zinc.

2.4 | The impact of zinc fertilizer on rice grain quality

Zinc (Zn) deficiency is considered one of the most widespread micronutrient issues in lowland rice soils (Fageria et al., 2002) and reduces productivity (Guo et al., 2016). Zn fertilizer is used to overcome this issue and has proven to increase crop yield and HRY (Fageria et al., 2011; Guo et al., 2016; Mollah et al., 2009). Zn fertilizer increases the availability of Zn to plants, thus increasing Zn uptake (Ghasal et al., 2016) and increases N absorption and grain crude protein content (Cakmak, 2008; Guo et al., 2016; Shi et al., 2010). Prior research has demonstrated that Zn fertilizer increases HRY (Ghasal et al., 2016; Gomaa et al., 2015), possibly due to an increase in protein content. Hasnain and Ali (2013) reported that Zn fertilizer increased amylose content and water absorption during cooking. Increased water absorption would increase starch granule swelling affecting pasting properties and cooked rice texture (Baxter et al., 2014). Guo et al. (2016) noted that Zn application increased 1,000-grain weight, which could indicate a change in amylose or amylopectin content as starch accounts for the majority of the grain. In contrast to Hasnain and Ali (2013), Ghasal et al. (2016) observed that Zn application had no significant impact on amylose content. However, their rates (1.25–5 kg/ha) were significantly lower (8–14 kg/ha) than the rates used by Hasnain and Ali (2013).

Zn fertilization can increase the Zn content of paddy (Fageria et al., 2011; Mollah et al., 2009) and milled rice (Ghasal et al., 2016). Zn deficiency in humans is prevalent in many regions where Zn-deficient soils are common (Cakmak, 2008). Increasing the Zn content of rice is essential for reducing Zn deficiency in humans, particularly in Asian countries where rice forms the staple diet (Shivay et al., 2008). Many Asian countries are expected to shift from self-sufficient producers in rice to net importers to sustain their growing populations. This shift may create an opportunity for growers producing rice of high Zn content. Rehman et al. (2012) stated there is a need for the examination of Zn fertilizer efficiency under different rice production systems and irrigation regimes. Currently, there is no published research on the impact of Zn fertilization on grain quality using the current Australian rice cultivars.

2.5 | The effect of plant density on rice grain quality

It is well established that plant densities between ~40 and 400 plants per m^2 do not differ significantly in rice yield (Ahmad et al., 2009; Ottis & Talbert, 2005). As the number of plants per square meter increases, panicle density increases but the number of filled grains per panicle decreases. At low densities, tillering increases with a higher percentage of filled grain and this compensatory behavior by the rice plant results in no significant difference in yield under differing plant densities. Rice grown at higher densities will experience greater competition for resources from neighboring plants compared with plants grown at lower densities; however, grain produced at low densities has increased competition for resources within the plant compared with grain produced in dense populations.

Few reports have investigated the effect of planting density on grain quality beyond its impact on HRY. Zhou et al. (2018) analyzed the quality parameters of rice grown at differing densities between ~35 and 80 plants per m^2 and reported that as density increased HRY decreased. Gravois and Helms (1996) investigated the effect of plant densities between 100 and 555 plants per m^2 on HRY and found that the response was cultivar specific. They reported a negative linear relationship between increasing plant density and HRY in two mid-season cultivars while there was a positive linear relationship observed in the two early-season cultivars studied. Mapiemfu et al. (2017) found an increased weeding frequency in African rice had a positive impact on HRY, likely due to a decrease in nutrient competition for the rice plant. Indeed, Soleymani and Shahrajabian (2011) reported a significantly lower grain weight (1,000-grains) in denser populations (25 plants per m^2). Changes to grain weight could occur due to variations in starch and its components, as previously mentioned.

Ahmad et al. (2009) measured the amylose content of rice grown at varying densities between 16 and 43 plants per m^2 and reported no significant differences. Zhou et al. (2018) noted that density had no effect on protein or amylose content but did influence the pasting properties. They found that the hybrid cultivar had a lower peak and trough viscosity, and a more positive setback at the higher density while the inbreed cultivar had a lower peak, trough, and final viscosity at the lower density. These RVA results suggest that processing and sensory quality may be influenced by plant density despite no change in protein or amylose content. Cai et al. (2011) attributed differences in pasting properties of two cultivars with similar amylose and protein contents to a possible difference in amylopectin structure. Indeed, prior research has demonstrated the importance of amylopectin fine structure on cooked rice texture (Li et al., 2016). Thus, the difference in pasting properties between plant densities observed by Zhou et al. (2018) may have occurred due to a possible change in amylopectin structure.

Other than Gravois and Helms (1996), research evaluating the effects of plant density on grain quality has assessed densities below the minimum threshold for achieving a high yielding crop in Australia. The target plant population density for rice is in the range of 100–200 plants per m^2 (Dunn et al., 2020). The appropriate sowing rate to achieve this density is influenced by factors such as sowing method and cultivar. Furthermore, only a proportion of seeds sown will successfully establish (30%–60% on average). In the temperate rice-growing regions of southern Australia, high grain yields are still attained with a plant population of 30 plants per m^2 if poor establishment occurs (Dunn et al., 2020); however, yields will decline at a density below 30 plants per m^2. The highest plant densities used in Soleymani and Shahrajabian (2011), Ahmad et al. (2009), and Zhou et al. (2018) were 25, 48, and ~80 plants per m^2, respectively, and are thus not appropriate for comparisons with large-scale growing systems as plants in large-scale systems grow in thicker densities between 100 and 200 plants m^{-2}. At 100–200 plants per m^2, there would be greater competition for resources for plants and individual grains within each plant than that found in the prior studies (Ahmad et al., 2009; Soleymani & Shahrajabian, 2011; Zhou et al., 2018) and hence possibly cause a greater impact on grain quality.

The prior studies (Ahmad et al., 2009; Gravois & Helms, 1996; Soleymani & Shahrajabian, 2011) assessing the impact of sowing rate on grain quality all tested long grain cultivars. Zhou et al. (2018) examined the difference between Chinese inbred and hybrid *japonica* cultivars; however, the grain type of these cultivars was not identified. Australia mainly grows short and medium grain *japonica* pure-line cultivars, and at the time of writing, there are no data on the impact of plant density on these grain types.

3 | IMPACT OF TEMPERATURE ON RICE GRAIN QUALITY

Temperature stress during the reproductive growth stages significantly impacts rice grain quality. High temperature during the reproductive period reduces the productivity and functionality of enzymes responsible for the transport of carbon/starch to the developing grain (Counce et al., 2005; Siebenmorgen et al., 2013). One study found a decline in the activity of key starch synthesizing enzymes as temperatures increased from 20°C to 40°C during grain development (Jin et al., 2005). Several reports found a significant decrease in amylose content of rice grown at elevated temperatures, altering gel consistency (Aboubacar et al., 2006; Yamakawa et al., 2007; Zhong et al., 2005).

In a controlled-climate experiment, Zhong et al. (2005) observed a deterioration in the processing and sensory qualities of rice exposed to elevated temperatures during grain filling. They reported that starch became more densely packed under higher temperatures which increased the gelatinization temperature for all cultivars (Zhong et al., 2005). Aboubacar et al. (2006) reported a higher proportion of short-chain amylopectin and a lower proportion of long-chain amylopectin in rice grown in the cooler rice-growing region of the United States, compared to rice grown in the warmer areas. Furthermore, during elevated temperatures, starch granule formation within the grain's endosperm was distorted (Aboubacar et al., 2006). Starch gelatinization properties are strongly affected by amylopectin fine structure (Aboubacar et al., 2006). A higher proportion of short chains of amylopectin is positively associated with the stickiness of cooked rice (Li et al., 2016).

Yamakawa et al. (2007) reported that chalky grains, developed at high temperatures, have endosperms with large air pockets with loosely packed starch granules. Along with chalkiness, elevated temperatures increase the likelihood of grain breakage during milling. The high solar radiation during ripening causes grain moisture to decline rapidly. Grains with low moisture dry further during the day and rewet at night-inducing fissuring, which causes grain breakage during milling (Kunze, 2001).

While increased temperature during reproductive growth decreases amylose content, the opposite effect on protein has been described. Jin et al. (2005) reported an increase in protein content of rice produced under elevated temperatures during grain development. Similarly, Chen et al. (2017) observed that higher temperature during grain filling increased the accumulation of most storage proteins, however, noted a decrease in prolamin content.

Increased temperature during reproductive growth has been found to increase the total lipid content of rice (Lanning et al., 2012). While higher day temperatures significantly impact grain quality, high nighttime air temperatures (NTAT) will also influence quality. Weather data analyzed over 17 years revealed that high NTAT during grain filling explained 26% of the variability in HRY (Cooper et al., 2006). Lanning et al. (2012) reported that peak viscosity and gelatinization temperature linearly increased and setback viscosity decreased as NTAT increased. Siebenmorgen et al. (2013) discussed the impact of high NTAT on grain quality in further detail.

Colder temperatures during reproductive growth will alter the physicochemical composition of the grain affecting quality. Cold stress reduces the rate and alters the duration of grain filling, which increases the frequency of abortive and shriveled grains (Arshad et al., 2017). In addition to changes in amylopectin structure as previously mentioned (Aboubacar et al., 2006), amylose content is also affected by colder temperatures and can increase by 20% when rice is exposed to low temperatures during grain development (Ahmed et al., 2008). The 20% increase in amylose content caused by low temperature in Ahmed et al. (2008) study changed the classification of rice from an intermediate amylose content (20%–25%) to a high amylose content (>25%) which would greatly influence cooked rice texture (Juliano, 1979).

Cold stress reduces the translocation of carbohydrates to the developing grain but increases the duration of the ripening stage, leading to a greater final carbohydrate accumulation within the grain (Kealey & Clampett, 2005). Ahmed et al. (2008) reported that although low temperature prolongs the duration of grain filling, final grain weight was unaffected. Protein content in rice has been shown to decrease in colder temperatures where one study reported a reduction in protein content of delayed sown rice which they associated with lower temperatures (Tsai et al., 2001). However, the amylose content of delayed sown rice increased, which may be associated with a greater carbohydrate/starch synthesis diluting the protein content.

Dong et al. (2011) demonstrated that high temperature stress during the initial grain filling stage (8–18 days postflowering) had a greater effect on grain quality than during the mid-filling stage (18–28 days postflowering). They observed an increase in chalkiness and a decrease in the amylose content of grains exposed to high temperatures during initial grain filling. Similarly, Chen et al. (2017) reported that temperature stress during flowering had a greater effect on the accumulation and composition of proteins when compared to stress during grain filling. These researchers and others (Zhong et al., 2005) reported that the response of grain quality to temperature stress is cultivar dependent. Lanning et al. (2012) hypothesized that the differences between cultivars in response to temperature stress were the result of different development patterns among cultivars.

3.1 | Reproductive timing and duration altered by agronomic practices

Crop management practices change the duration and timing of particular growth stages affecting the thermal environment at which they usually occur. Australia's growing season is characterized by long days and high levels of solar radiation with low temperatures at the beginning and end of the season. Sowing too early will not only affect plant establishment from colder temperatures at the start of the season, but grain quality will also be affected by warmer temperatures during grain filling. Late sowing will impact crop yield and grain quality from cooler temperatures at microspore and grain filling, respectively.

Dunn and Gaydon (2011) reported a 12- to 16-day delay of pollen microspore in rice grown using DPW when compared to conventional irrigation. Furthermore, they found that increasing N rate extended the time taken for the rice to reach flowering and physiological maturity (Dunn & Gaydon, 2011). The delay in microspore pushes this critical growth stage outside the window of the highest probability of safe minimum temperatures, which can cause sterility (Gunawardena & Fukai, 2005) whereas the delay in physiological maturity moves harvest into unfavorable conditions, causing delays and further in-field drying and rewetting inducing grain fissuring (Kunze, 2001).

Plant population also changes the duration and timing of particular growth stages. Gravois and Helms (1996) reported that excessive tillering, found in lower plant densities, lengthens the grain filling period, which can indirectly reduce HRY (Jongkaewwattana & Geng, 2001). Furthermore, grain grown at lower densities will mature faster from increased solar radiation due to less mutual leaf shading, which enhances the risk of shattering and predation from birds. The loss of high-quality mature grains results in an increased proportion of lower quality grain at harvest, lowering HRY (Grigg et al., 2016).

Timely sowing ensures optimal plant growth and development during a period of suitable temperatures and high levels of solar radiation. Sowing outside the "ideal" planting window will alter the temperature at which critical reproductive growth stages occur, affecting grain quality. Ghosh et al. (2004) reported a reduction in HRY and amylose content in late sown rice during India's dry season, due to higher ambient temperatures occurring during grain development. During the wet season, Kaur et al. (2016) found a greater accumulation of amylose in delayed sown rice which they attributed to lower night air temperatures during starch synthesis.

4 | INTERACTION BETWEEN GENOTYPE, ENVIRONMENT, AND AGRONOMIC MANAGEMENT

Understanding the physiological behavior of each cultivar is important for predicting grain quality. The rate of flowering and the number of days between heading and maturity have shown to have a significant effect on HRY (Tab ien et al., 2009). Tab ien et al. (2009) reported cultivars that reached the heading stage earlier had a shorter flowering duration and cultivars with a shorter flowering duration had a higher HRY. Furthermore, as the number of days between heading and maturity increased, HRY increased. Late maturing cultivars produce more dry matter from a higher rate of solar radiation, which reduces plant N concentration, resulting in a lower grain protein content than found in early maturing cultivars (Perez et al., 1996; Tsukaguchi et al., 2016). These findings contrast typical plant behavior under N fertilizer management where high doses of N increases vegetative dry matter and plant N concentration increasing grain protein content.

Agronomic and environmental factors will influence grain quality differently depending on the cultivar. Cultivars vary in protein content and composition (Balindong, Ward, Liu, et al., 2018; Perez et al., 1996) and show substantial differences in protein content response to N management (Kaur et al., 2016; Ning et al., 2009; Perez et al., 1996; Tsukaguchi et al., 2016). Chen et al. (2017) reported the effect of temperature stress on individual protein fractions differed between cultivars. The effect of N application on amylose content also varies between cultivars (Kaur et al., 2016). Changes to both protein and amylose content will affect the pasting and thermal properties of rice, as previously discussed.

Genetics, location, and crop year can contribute to variations in rice molecular and physical properties (Cameron et al., 2008). Cameron et al. (2008) investigated the differences in Californian and Arkansas cultivars grown separately and in the same region. When grown separately, Arkansas cultivars had higher lipid and protein content but lower amylose compared to the Californian cultivars; however, when grown in the same region, the differences in quality parameters decreased.

Changes in physical characteristics in response to N management vary between rice lines. Using different US cultivars, Grigg et al. (2016) observed a reduction in grain length with increased N, whereas another study found a slight increase in grain length (Mahajan et al., 2011). Leesawatwong et al. (2005) also noted that differences in HRY in response to N were cultivar dependent. Ning et al. (2010) reported that prolamin and glutelin were primarily determined by N management, while albumin and globulin were controlled by genetics. Islam et al. (1996) reported a greater response in total protein and protein fractions to N from *indica* cultivars compared to *japonica*. The distribution of proteins between brown and milled rice also varies between cultivars (Ning et al., 2010).

Cheng et al. (2003) reported that the impact of water-saving measures on grain quality was cultivar dependent and milling and cooking quality decreased in some cultivars. Gravois and Helms (1996) observed a significant interaction between planting density, HRY and cultivar and concluded that HRY response to plant density should be assessed on a cultivar by cultivar basis.

5 | CONCLUSION

Particular genes that control grain quality traits which breeding programs can utilize are well researched (Fitzgerald et al., 2009). However, the time taken from initial cross to release of a new cultivar can take up to ten years while environmental conditions and market needs can change drastically between years. Developing new cultivars for the changing market and environment is necessary. However, refining management practices for current cultivars is vital for reducing the variability in grain quality. This review highlights that variation in crop management can alter rice grain quality and the response of any one cultivar to the long list of variables is unique to that cultivar. Thus, extensive field testing is required to optimize the quality of each cultivar. Future research examining the effects of agronomic management on rice quality needs to consider that differences in management will alter the duration and timing of particular growth stages affecting quality and keep an awareness that results could be affected by differences in climate during grain ripening. The monitoring of plant flowering would indicate if there was a delay in any growth stages.

This review demonstrates the unique management practices of Australian grown rice and draws attention to the lack of research assessing the effect of agronomic management on grain quality in Australia. Internationally, research assessing the effects of agronomic management practices on grain quality has focused primarily on HRY. While recent research has documented the impact of crop management on amylose and protein content, starch structure, and protein composition, the impact of these on end-use functionality has been given little attention. There is a particular need for research into the impact of agronomic management on the end-use functionality of rice, such as processing and sensory quality. Investigating how specific cultivars interact with agronomic practices will provide better recommendations to rice farmers, reducing the variability in grain quality found within the rice industry. A significant challenge for rice growers in Australia and globally is to reduce water usage without impacting crop yield and grain quality. Targeted breeding programs, in combination with agronomic research, should be used in conjunction to address this issue.

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ORCID

Rachael Maree Wood https://orcid.org/0000-0003-4858-6015
Prakash Oli https://orcid.org/0000-0002-4124-8999

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