Research Article

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Impact of production practices on physicochemical properties of rice grain quality††

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Abstract

BACKGROUND: Rice growers are interested in new technologies that can reduce input costs while maintaining high field yields and grain quality. The bed-and-furrow (BF) water management system benefits farmers through decreased water usage, labor, and fuel as compared to standard flood management. Fertilizer inputs can be reduced by producing rice in rotation with soybeans, a nitrogen-fixing crop, and with the use of slow-release fertilizers that reduce nitrogen volatilization and run-off. However, the influence of these cultural management practices on rice physicochemical properties is unknown. Our objective was to evaluate the influence of nitrogen fertilizer source, water management system, and crop rotation on rice grain quality.

RESULTS: Grain protein concentration was lower in a continuous rice production system than in a rice–soybean rotation. Neither amylose content nor gelatinization temperature was altered by fertilizer source, crop rotation, or water management. BF water management decreased peak and breakdown viscosities relative to a flooded system. Peak and final paste viscosities were decreased by all fertilizer sources, whereas, crop rotation had no influence on the Rapid Visco Analyser profile.

CONCLUSION: Sustainable production systems that decrease water use and utilize crop rotations and slow-release fertilizers have no major impact on rice physicochemical properties.
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Keywords: *Oryza sativa* L.; rice grain quality; rice; crop rotation; rice fertilization; rice irrigation

INTRODUCTION

Processing and cooking quality of rice (*Oryza sativa* L.) is important because it determines the acceptability of rice for both export and domestic markets.[1,2] Consumers in North and South America, southern China, and Europe prefer rice that has an intermediate (70–74 °C) gelatinization temperature and apparent amylose (200–240 g kg^{-1}) concentration and is firm and fluffy after cooking.[1] Conventional US long-grain rice cultivars are bred to have these cooking quality characteristics. Any change in production practices that alters the physicochemical properties of rice may impact acceptance in domestic and global markets. Rice farmers in the USA have been quick to adopt new production technologies and rice yields have increased by an average of 1% annually over the last 20 years. However, farmers have to ensure that changes in management procedures do not alter grain quality and impact market opportunities.

Recently, due to dramatic spikes in fuel prices, fertilizer and irrigation pumping costs have increased, resulting in farmers' increased interest in ways to control production costs while maintaining high yields. One way to reduce irrigation costs is by growing rice under a bed-and-furrow (BF) system. This management is similar to that used for maize and soybeans, where the rice is planted in raised beds and irrigated through furrows that follow the slope of the land.[3] Besides improving water use efficiency, there are additional savings in fuel and labor through the elimination of levees needed in flooded rice paddies.[3] Other potential benefits of growing rice under BF management include greater flexibility in applying fertilizer, herbicides, and pesticides that can be timed with the irrigation. However, Vories *et al*.[3] and Hefner and Tracy[4,5] reported that potential disadvantages associated with the BF system included increased insect, weed and disease pressure, increased nitrogen losses through volatilization, and lower grain yields.

Over the past 10 years, research in the public and private sector has resulted in the development of herbicide resistance technology and hybrid rice.[6] In 2002, Clearfield® hybrid rice was released for commercial production in the southern USA.[7] Clearfield® rice is resistant to the herbicides imazethapyr and

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imazamox that are used to control a broad spectrum of weeds, including red rice (*Oryza sativa* L.), which is the most costly weed to control in rice production.[6] As new herbicide-resistant cultivars and hybrids have become available to farmers, their use in flooded and non-flooded systems has increased to over 40% of the acreage in the southern USA.[8]

The primary nitrogen (N) source used by rice farmers is urea ($NH_2-CO-NH_2$), which is water soluble and readily available for plant uptake. However, when urea is left on the soil surface and exposed to moist conditions, urease converts it to ammonium and carbon dioxide, which are lost before they can be utilized by the plant.[9] In order to minimize N losses due to volatilization, rice farmers apply urea to a dry soil surface at the four- to five-leaf stage and immediately flood the field. In a BF management system, a permanent flood is never achieved; thus the use of slow-release fertilizers or coated urea is a management option for reducing N losses due to volatilization. Agrotain® (urea coated with *N*-(*n*-butyl)thiophosphoric triamide (NBPT)), is a urease inhibitor that reduces ammonia volatilization by stabilizing the urea and inhibiting the hydrolytic action of urease. Sulfur-coated urea is manufactured by coating urea with sulfur and sealing it with polyethylene oil or microcrystalline wax. Nitrogen diffuses through the pores of the coating, slowing its availability to the plant. Slow-release fertilizer appears to be effective when applied to the soil surface, making it potentially ideal for rice production using the BF system.[10]

With the development of new high-yielding, herbicide-resistant cultivars and the availability of controlled-release urea products, planting rice using the BF system has become more attractive, especially on sloped terrain that would otherwise require a large number of levees for water management. Rice acreage planted using the BF system has increased in Arkansas from less than 405 ha in 2002 to more than 3240 ha in 2007.[11]

Crop rotations are used by farmers to enhance the control of rice insect and disease pests along with red rice. In Arkansas, where ~50% of the rice in the USA is grown, soybeans (*Glycine max* L.) are the most common rotation crop, providing additional benefits of nutrient enhancement as a result of N fixation. Rice under flooded production that is grown in rotation with corn and soybeans has been shown to have higher yield as compared to a continuous rice system.[12] Because corn and soybeans are commonly grown as row crops, there is an added advantage of growing rice under the BF system when in rotation with these crops. Once beds are formed for the row crop it is not necessary to level the field and establish levees for the rice rotation.

Studies have shown that different crop rotations and fertility inputs can influence protein concentration, pasting viscosity profiles and sensory attributes of rice grown under flooded conditions.[13–17] However, as growers adopt new production systems that make more efficient use of irrigation and fertilizer inputs, it is important to know how these practices impact rice processing and cooking quality. The objective of this study was to evaluate the influence of crop rotation, irrigation management, and nitrogen fertilizer source on rice physicochemical factors associated with grain quality.

MATERIALS AND METHODS

Location and cultivars

Two studies were conducted near Stuttgart, AR, USA, at the Dale Bumpers National Rice Research Center/University of Arkansas Rice Research and Extension Center on a Dewitt silt loam soil (fine, smectitic, thermic, Typic Albaqualf) during 2006–2008. In 2006, Clearfield® XL-730 hybrid rice was used and in 2007 and 2008 this was replaced with Clearfield® XL729 because the previous hybrid was no longer commercially available (all seed courtesy of RiceTec Inc., Alvin, TX, USA). Both cultivars are commercially acceptable long grains, having an intermediate amylose concentration (~203 g kg^{-1}) and intermediate gelatinization temperature (72 °C).

Experimental design

Study 1 (fertilizer source × irrigation method; 2006 and 2007)

Rice was planted in continuous rice rotation that was managed using either a flood or BF system. In the BF system, beds were formed in a 6 m × 45 m plot using a 6.4 m bedder (Eddins Manufacturing Inc., Stuttgart, AR, USA) with furrow coulters placed at 76 cm intervals. The beds were 10 cm high and the rice was drill seeded on the beds and in furrows at a rate of 39 kg ha^{-1} using an Almaco no-till drill (Almaco, Nevada, IA, USA). Flooded plots were sown at the same rate and using the same row spacing as the BF plots. In this study, four fertilizer treatments were used: (1) no fertilizer (NF); (2) urea; (3) Agrotain® (Ag); and (4) sulfur-coated urea (SR). A uniform nitrogen rate of 135 kg N ha^{-1} was applied as a single application at the four- to five-leaf stage using urea, Agrotain®, or sulfur-coated urea. A split-plot design with four replications was used with irrigation method as the main plot treatment and fertilizer source as the sub-plot.

Study 2 (crop rotation × irrigation method; 2006, 2007, and 2008)

Agrotain® at a rate of 135 kg ha^{-1} was the sole N fertilizer source in plots that were either flooded or BF-managed using two crop rotations: (1) continuous rice (R/R); and (2) rice following soybeans (R/SB). A split-plot design with four replications was used with rotation as the main plot and water management as the sub-plot. Water was applied to the BF plots in the furrow at 7- to 10-day intervals and allowed to flow to the bottom of the sloped field, where it was drained away. For the flooded system, a permanent flood was applied immediately following the fertilizer application and held to a depth of 10 cm until physiological maturity[18] and then drained.

Sampling

Rough rice samples were collected from each plot at harvest maturity, cleaned using an Almaco seed cleaner (Allen Machine Co., Nevada, IA, USA), and dried at 35 °C to 120 g kg^{-1} moisture concentration. The average moisture concentration over all treatments was 121, 136, and 129 g kg^{-1} for 2006, 2007, and 2008 respectively. Samples were then stored at 4 °C and 50% relative humidity until dehulling and milling. Brown rice was produced by dehulling rough rice using a Satake Testing Husker (Satake Engineering Co., Uino Taito-Ku, Tokyo, Japan). This was followed by milling with a McGill No. 2 mill (Grain Machinery Mfg. Corp., Miami, FL, USA) and whole milled kernels were separated from the broken kernels using a Grainman shaker table (model #61-115-60 Hz, Grain Machinery Mfg. Corp.) with #10 screens. The milled samples were ground in a Cyclotech grinder (Foss North America, Eden Prairie, MN, USA) containing a 0.5 mm screen. All analytical tests using these flour samples were conducted in duplicate.

Amylose, Rapid Visco Analyser (RVA), and protein analyses

Apparent amylose concentration was determined by the method of Williams *et al.*,[19] using an AutoAnalyzer[20] (Seal Analytical, Inc.,

Mequon, WI, USA), and AACC method 61-03,[21] while pasting properties were determined according to AACC method 61-02[21] using an RVA (model 4, Newport Scientific, Eden Prairie, MN, USA) with Thermocline for Windows software (version 2.2). Pasting properties included: (1) peak viscosity = max. viscosity during heating; (2) trough = hot paste viscosity, (3) breakdown = peak – trough viscosity; (4) final viscosity = cold paste viscosity; and (5) setback = final – trough viscosity. Viscosity was measured in Rapid Visco Units (RVU), with one RVU equaling approximately 12 centipoises. Nitrogen concentration was determined on ground brown (unmilled) rice using a Leco FP-2000 Nitrogen Analyzer (LECO Corporation, St Joseph, MI, USA), analyzed in duplicate, and reported as protein, using 5.95 as a conversion factor.

Differential scanning calorimetry (DSC) analysis

Thermal properties were determined using a differential scanning calorimeter (model 4100, Calorimetry Sciences Corp, Spanish Fork, UT, USA). The system contains a reference cell and three sample cells. One milligram of rice flour and 2 mg water (1 : 2) were placed in a Hastelloy ampoule and subjected to one heating cycle. Samples were heated from 20 to 150 °C at a heating rate of 1.5 °C min^{-1}. Baseline subtractions were made on thermal curves. Thermal curves depicting starch gelatinization were characterized by three temperatures: gelatinization onset temperature (T_o) (onset of peak development), peak temperature (T_p) (temperature at which maximum heat flow occurred during the scanning cycle) and conclusion (T_c) (taken at the conclusion of peak development). The enthalpy associated with starch gelatinization (ΔH) was determined by drawing a line between (T_o) and (T_c) and determining the area under the curve. Enthalpy was expressed as J g^{-1} on a dry weight basis of rice flour. T_p was used to indicate the gelatinization temperature.

Statistical analysis

Study 1

The fixed treatment effects were fertility source (sub-plot) and irrigation (main plot). The variety within year and block were random effects.

Study 2

The fixed treatment effects were crop rotation (main plot) and irrigation method (sub-plot). Year, variety within year and block were random effects. The GLIMMIX procedure in SAS (Version 9.1.3, Cary, NC, USA) was utilized to fit statistical models for each measured grain quality response in both studies. If the fixed effects exhibited significant *P*-values of <0.05, multiple comparison tests were performed using the difference of LSMEANS option. The *P*-values for the multiple comparison tests were corrected via the Tukey–Kramer adjustment.

RESULTS AND DISCUSSION

Protein concentration

Study 1

There was a significant difference ($P < 0.05$) in protein concentration due to the addition of fertilizer (Table 1). Without nitrogen fertilizer (NF), the LS Means for protein concentration was 69.1 ± 5.6 g kg^{-1}, whereas, with the application of nitrogen, the LS Means increased to ~79 g kg^{-1} (Table 2). Fertilizer source did not alter the protein concentration. Thus the availability of N for uptake by the plant appeared to be the same regardless of whether urea was used or fertilizer products that were developed to prevent loss due to volatilization. Although protein concentration was lower for the BF system than in the flood system (76.6 and 77.0g kg^{-1}, respectively), it was not significant at $P < 0.05$; thus, planting rice using the BF system has less influence on protein concentration than insufficient N. Cheng *et al*.[22] tested three water management systems using three rice cultivars, and found that protein concentration was significantly influenced by water management but that the response depended more on genotype than water management system. Perez *et al*.[23] tested six different N sources individually and in combination and found that protein concentration was influenced by N fertilizer source, but to different degrees depending on genotype. They also reported that protein concentration was lowest in plots where no N was applied.

Study 2

Protein concentration was altered by crop rotation (Table 3). Though not significant at $P < 0.05$, the LS Means for the protein concentration of BF rice was higher than that of flooded rice: 80.0 to 77.6 ± 2.9 g kg^{-1}, respectively (Table 4). Continuous rice significantly ($P = 0.034$) decreased protein concentration when compared to the rice/soybean rotation: 76.1 g to 81.5 ± 2.9 g kg^{-1}, respectively (Table 4). These results indicate that growing rice under BF had less impact on protein concentration than crop rotation.

Apparent amylose

Apparent amylose and protein concentrations in the grain can change the texture of cooked rice and the RVA profile.[16,24,25] Research has shown that apparent amylose and protein concentrations can be altered by N application.[16,23] Study 1 showed that apparent amylose concentration was not influenced by the addition of N fertilizer or the N fertilizer source (Table 1). Study 2 showed that neither crop rotation nor irrigation method changed the apparent amylose concentration (Table 3). The LS Means for apparent amylose concentration across all treatments ranged from 202 ± 3.6 g kg^{-1} for rice grown in flooded conditions in Study 2 to 210 ± 2.6 g kg^{-1} for rice grown using SR nitrogen in Study 1. Changes in apparent amylose concentration due to N application reported in other studies may be due to cultivars or fertility treatments used. Cheng *et al*.[22] found that variance in apparent amylose concentration was mainly attributed to genotype and not water management. Perez *et al*.[23] found that apparent amylose concentration was altered by fertilizer treatment but stated that the change was not consistent.

Rapid Visco Analyser

RVA parameters (peak viscosity, trough viscosity, final viscosity, breakdown, and setback) are indicators of processing and cooking qualities.[26] Study 1 showed that adding fertilizer had a significant ($P < 0.05$) impact on the RVA profile (Table 1). Applying N decreased all RVA parameters, whereas RVA parameters were not statistically different among fertilizer N sources (Table 2). Of the different N sources tested, peak, final, and breakdown viscosities LS Means values were lowest for SR (221 ± 43, 212 ± 28, and 114 ± 21 RVU, respectively) and highest for urea (224 ± 43, 226 ± 28, and 121 ± 21 RVU, respectively). Regardless of N source, final and setback viscosities with the addition of N were lower with LS Means ranging from 212 to 214 ± 28

Table 1. Summary of analysis of GLIMMIX results for apparent amylose concentration, protein concentration, DSC and RVA parameters in response to irrigation method and fertility source as seen in Study 1[a]

			DSC[b]				Rapid Visco Analyser analyses[c]				
Source of variation	Apparent amylose	Protein	Onset temp.	Peak temp.	Final temp.	ΔH	Peak visc.	Trough visc.	Final visc.	Breakdown	Setback 1
Irrigation (*I*)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fertilizer source (*F*)	NS	<0.001	NS	NS	NS	NS	0.027	0.059[d]	<0.001	0.021	<0.001
$I \times F$	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Probability values $>P = 0.05$ are shown as non-significant (NS).
[b] DSC, differential scanning calorimetry; Onset temperature., peak temperature; final temperature; ΔH, transition enthalpy.
[c] Breakdown, peak hold; Setback 1, final – trough viscosity. 1 RVU = ~12 centipoises.
[d] Although not significant at $P < 0.05$, the *P*-value is shown because it indicates a trend.

Table 2. Least square means comparison using Tukey–Kramer grouping for protein concentration and RVA parameters seen in Study 1[a]

		Rapid Visco Analyser analyses[b] (RVUs)				
Main effect	Protein (g kg^{-1})	Peak visc.	Trough visc.	Final visc.	Breakdown	Setback 1
Flood	77.0A	230A	111A	218A	119A	106A
Bed-and-furrow	76.6A	222A	108A	214A	114A	106A
NF[c]	69.1A	235A	115A	226A	121A	111A
Urea	79.9B	224AB	109A	214B	116AB	105B
Ag	78.8B	223AB	109A	213B	115AB	104B
SR	79.4B	221B	109A	212B	114B	104B

[a] Values having the same letter in the same section and in the same column are not significantly different at $P < 0.05$.
[b] Breakdown, peak hold; Setback 1, final – peak. 1 RVU = ~12 centipoises.
[c] AG, Agrotain-coated urea; NF, unfertilized; SR, slow release (sulfur-coated urea); Urea, uncoated urea.

RVU and 104–105 ± 7 RVU, respectively, than when no N was added: 226 ± 28 RVU and 111 ± 7 RVU, respectively. Water management did not alter any of the RVA parameters at the $P < 0.05$ level, although the LS Means values were numerically less under BF than under flooded conditions (Table 2). Study 2 showed that the only RVA parameter significantly altered by water management when comparing crop rotation was breakdown viscosity. Planting rice on beds decreased breakdown viscosity as compared to the flooded system ($P = 0.045$) (Table 4). Crop rotation had no influence on any of the RVA parameters (Table 3). Research has shown that changes in the RVA profile can be attributed to changes in protein concentration.[25] This may explain why no changes in the RVA profile were present when comparing N fertilizer sources, since protein concentration did not differ. However, differences were present when no fertilizer was added and protein concentration was significantly lower (Table 2). This does not explain why there were no changes in RVA parameters between crop rotations where protein concentrations were significantly ($P < 0.05$) different but changes were present in the BF *versus* flooded comparison where protein was not significantly ($P > 0.05$) different (Table 4). From this we conclude that other factors, such as starch structure, may have played a part in influencing RVA parameters. Rice starch is made up of two macromolecules – amylose (0–30%) and amylopectin (70–100%)[27] – and research has shown that the long chains of amylopectin have a negative correlation on breakdown viscosity, whereas the short chains are positively correlated.[28] Therefore water availability may have influenced the chain lengths of the amylopectin molecule.

Differential scanning calorimetry

The DSC profile is used to determine the temperature at which gelatinization occurs (peak temperature) and how much energy is required during gelatinization (enthalpy, ΔH).[11,27,29] Studies 1 and 2 showed that neither N source, crop rotation, nor water management had a significant influence ($P > 0.05$) on gelatinization temperatures (Tables 1 and 3). Onset and final temperatures were 70.9 and 94.6 °C, respectively, with a peak temperature at 81.4 °C. Neither N source, crop rotation, nor water management had an influence on ΔH (9.6 J g^{-1}). No interactions for this parameter were detected in either study.

CONCLUSIONS

Growing rice using BF water management had little influence on physicochemical factors associated with cooking and processing quality. Only in one study was there some impact on pasting viscosity and breakdown, but it was not liable to alter processing quality. The addition of N fertilizer increased protein concentration and was associated with changes in RVA parameters, but not DSC profiles. However, using coated urea fertilizers in lieu of uncoated urea did not significantly change the protein concentration or factors associated with processing quality. Similarly, there was little difference in cooking and processing traits observed between the two crop rotations, except for protein concentration. Planting rice using BF management has been shown to be beneficial to farmers by saving water and labor costs and our study, involving hybrids which have conventional long-grain cooking quality, indicates that there is little impact on rice grain cooking or processing qualities

Table 3. Summary of GLIMMIX results for apparent amylose concentration, protein concentration and RVA parameters in response to irrigation method and crop rotation as seen in Study 2[a]

			DSC[b]				Rapid Visco Analyser analyses[c]				
Source of variation	Apparent amylose	Protein	Onset temp.	Peak temp.	Final temp.	ΔH	Peak visc.	Trough visc.	Final visc.	Breakdown	Setback 1
Rotation	NS	0.034	NS	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation method	NS	NS	NS	NS	NS	NS	0.096[d]	NS	NS	0.045	NS
Rotation × irrigation	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Probability values $>P = 0.05$ are shown as non-significant (NS).
[b] DSC, differential scanning calorimetry; Onset temperature., peak temperature; final temperature; ΔH, transition enthalpy.
[c] Breakdown, peak hold; Setback 1, final – trough viscosity. 1 RVU = ∼12 centipoises.
[d] Although not significant at $P < 0.05$, the P-value is shown because it indicates a trend.

Table 4. Least square means comparison using Tukey–Kramer grouping for protein concentration and RVA parameters seen in Study 2[a]

		Rapid Visco Analyser analyses[b] (RVUs)	
Main effect	Protein (g kg^{-1})	Peak visc.	Breakdown
Continuous rice	76.1A	215A	113A
Rice/soybeans	81.5B	211A	109A
Flood	77.6A	217A	114A
Bed-and-furrow	80.0A	209B	108B

[a] Values having the same letter in the same section and in the same column are not significantly different at $P < 0.05$.
[b] Breakdown, peak hold viscosity. 1 RVU = ∼12 centipoises.

as compared to flooded management. This demonstrates that farmers have flexibility in using cultural management systems that reduce production costs and save resources without negatively impacting rice cooking and processing quality.

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