INVESTIGATION OF IRRI TEST TUBE MILL OPERATING PARAMETERS

R. C. Bautista, T. J. Siebenmorgen, R. M. Burgos, A. Mauromoustakos

ABSTRACT. *The objective of this study was to optimize the operating parameters of the International Rice Research Institute (IRRI) Test Tube rice mill. The goal was to minimize the milling duration required to attain a milling degree equivalent to a 12% brown rice kernel mass loss. Operating parameters including brown rice mass, milling duration, tube oscillation frequency, and test tube size were investigated with the brown rice kernel mass loss as the response variable. Two rice cultivars, Bengal (medium−grain) and Cypress (long−grain), at 12.5 and 12.1% MC, respectively, were used for the tests. Results indicated that milling with the IRRI Test Tube mill was significantly affected by brown rice mass, milling duration, tube oscillation frequency, and the tube head space. A strategy to set up a milling procedure for optimum parameter combination to attain a 12% brown rice mass loss percentage was proposed. The results provide a guide to users, particularly rice breeders and physiologists, in the selection of proper parameters for removing the bran from small brown rice samples.*

Keywords. *Rice, Brown rice, Milling, Laboratory rice mill.*

An ideal rice mill removes the bran layers and germ from brown rice kernels with minimal kernel breakage and preserving each kernel in its original shape (Webb, 1985). Typically, laboratory−scale rice mills such as the McGill No. 2 require brown rice samples of at least 120 g. Milling smaller rice samples for quality analyses has presented problems because of the lack of appropriate mills. Frequently, rice samples from breeding lines, ranging from approximately 2 to 10 g or even smaller quantities obtained from single or multiple panicles, are produced with a need to be milled in order to estimate milling quality. While there are an enormous number of small−quantity samples being generated from experimental test plots and breeding lines for milling quality estimation, there is no accepted laboratory mill that adequately provides an indication of milling quality. Such a mill would be extremely beneficial to rice breeders, cereal chemists, and plant physiologists.

In a recent effort to meet this need, milling performance of the Kett "Pearlest" polisher and the IRRI Test Tube mill were assessed relative to that of the McGill No. 2 lab mill. This study indicated the potential of the IRRI mill for milling small quantities of brown rice (Bautista and Siebenmorgen, 2002). However, the IRRI mill takes over 2 h and that needs to be reduced.

The American Association of Cereal Chemists (AACC) Rice Technical Committee established the kernel mass loss percentage (MLP) standard of 12% as an acceptable degree of milling (DOM) for milled rice. Bautista and Siebenmorgen (2002) reported that it took approximately 120 min to mill a long−grain rice cultivar Drew (at 12% MC −− moisture contents are expressed on a wet basis.) and about 180 min to mill a medium−grain Bengal (at 12% MC) to this DOM level in the IRRI mill. IRRI's data indicated shorter durations for the test tube mill (IRRI, 1987a). The discrepancy could be due to differences in DOM measurement (IRRI used a dye test), rice cultivar (IR 72, a long−grain indica cultivar), and the MC (about 14%) of the brown rice used. A given DOM can be achieved in a shorter milling duration with higher rice MCs (Andrews et al., 1992). This study investigated whether the operation of the IRRI Test Tube Rice mill could be improved to achieve shorter milling times.

EARLY MODELS OF "SMALL" SAMPLE SIZE TEST TUBE MILLS

The earliest "small−sample" test tube mill was developed in 1956 when Dr. Henry Beachell of IRRI built a machine to shake 20 test tubes containing brown rice samples mixed with quartz crystals as an abrasive agent (Scott et al., 1964a). The mill was developed for milling small quantities of rice from greenhouse or breeding studies when milling quality data was desired. This machine was used at the Regional Rice Quality lab in Beaumont, Texas, and at the Rice Experiment Station in Crowley, Louisiana (Scott et al., 1964b). The machine was improved by replacing quartz with fused aluminum oxide of 46 and 60 grit sizes in equal parts with the abrasive constituting one−third by weight of the sample. The mill reported by Scott et al. (1964a) had the following specifications: 390 r/min, 139−mm stroke length, 110−min milling duration, 1.5−kW motor, and occupied a space of 1.39 m^2. In 1970, Boonit and Devakul devised a similar machine using a single−cylinder horizontal piston engine. A wooden block with eight test tubes fixed within the block was attached to the

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piston, and a 0.746−kW electric motor was used to reciprocate the piston at 1000 r/min. This machine was claimed by Boonit and Devakul (1970) to accomplish milling in a shorter duration than that of Scott et al. (1964a) and occupied a space of 0.56 m^2.

The two early machines were bulky. They were noisy due to vibration requiring frequent lubrication and required long milling durations. For these reasons, Khan and Wikramanayake (1971) designed and developed at IRRI a high frequency vibration mill with two tube holders reciprocating in opposite directions at 1000 r/min. The model consisted of two tube holders with each holder containing 12 7−mL test tubes. A pair of vertically mounted fiberglass strips secured the tube holders. The mill was later known as the IRRI Test Tube mill. It was tested and modified in the mid 1980s to accommodate a larger number of tubes containing smaller masses of samples that were milled for shorter durations. The modified design was less bulky (occupied a space of about 0.3 m^2) than the previous version. It was reported that milling duration and the frequency and length of tube oscillation influenced milling performance (IRRI, 1987a). Using a dye to measure the milling degree for a long−grain variety at about 14% MC, a frequency of 1750 r/min was "sufficient" to mill a 3−g brown rice sample per tube in 20 min (IRRI, 1987b). That test, however, did not report a quantitative mass loss percentage (MLP) in milling brown rice.

Description of the Current IRRI Test Tube Mill

A schematic of the current IRRI Test Tube mill is shown in figure 1. The current version accomplishes milling by oscillating two wooden boxes vigorously in opposite directions with each box holding as many as 35 7−mL test tubes. The motion has an amplitude of approximately 16 mm and a frequency of approximately 1580 r/min. Each test tube typically contains approximately 3 g of brown rice and about 4 g of aluminum oxide, as described by Bautista and Siebenmorgen (2002). Bran removal from kernels is accomplished by the kernel−to−kernel friction and abrasive action induced by the aluminum oxide as the tubes are oscillated. The milling duration required to remove bran varies with rice variety and MC, which follows the findings of Andrews et al. (1992) using a McGill No. 2 mill. Milled rice is separated from the bran and aluminum oxide by using a sieving screen.

Objective

The goal of this study was to optimize the operation of the IRRI Test Tube mill for milling small quantity samples of medium− and long−grain brown rice cultivars using the AACC−established 12% MLP criteria as the response variable.

Materials and Methods

The electric motor and pulley of an IRRI Test Tube mill was replaced with an electric motor with a variable diameter pulley (89 to 127 mm diameter) to allow variation in oscillation frequency of the tube holders. Samples of rough rice cultivars Bengal (medium−grain) and Cypress (long−grain) were harvested from foundation seed plots of the University of Arkansas Rice Research and Extension Center at Stuttgart, Arkansas, in the fall of 2000 using a plot

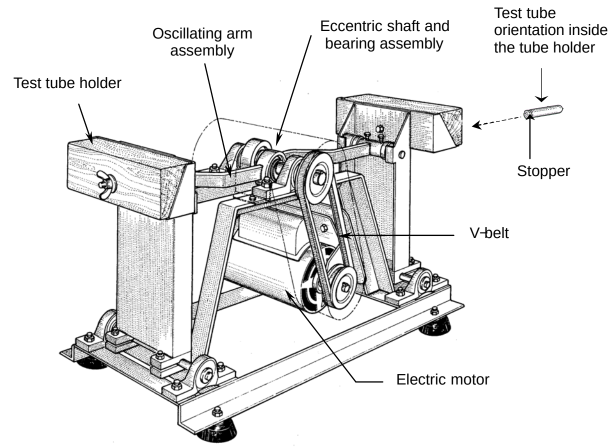
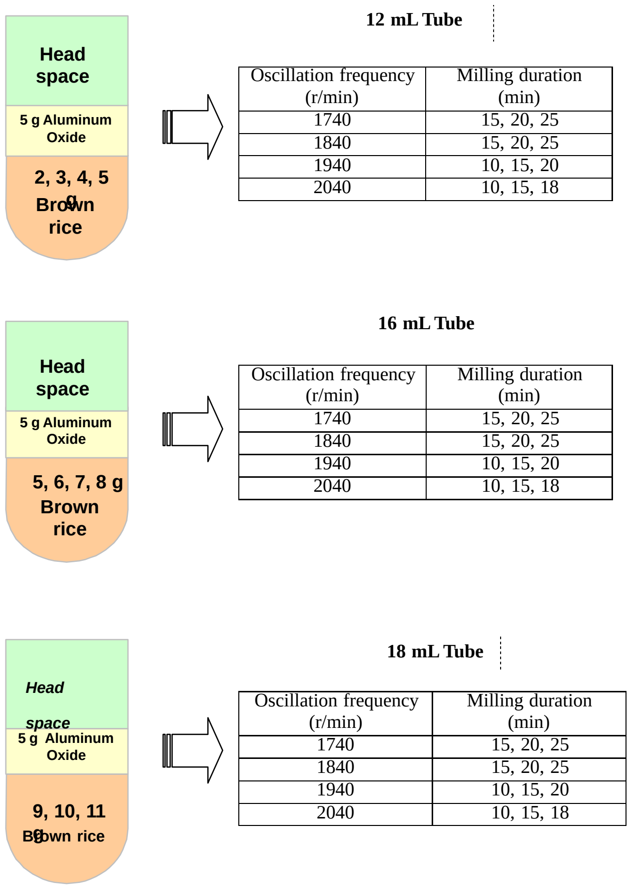


Figure 1. The IRRI test tube mill.

combine. Lot samples of Bengal and Cypress rough rice (10 kg each) were cleaned using a grain cleaner (MCi® Kicker Grain Tester, Mid−Continental Industries, Inc., Newton, Kans.) and conditioned in an environmental chamber to approximately 12.5% MC. After conditioning, the lot samples were placed in Ziploc® bags and placed inside a cooler maintained at approximately 4°C. Brown rice was prepared for each milling run by taking enough rough rice samples from the 4°C cooler, allowing the samples to equilibrate for 24 h to a lab temperature of approximately 21°C, and hulling. A laboratory huller (Type THU, Satake Co., Hiroshima, Japan) with a 0.48−mm clearance between the rollers was used for hulling all samples to obtain brown rice.

Figure 2 shows the experimental design for evaluating the operation of the IRRI Test Tube mill. Using the MLP as a response parameter, the following parameters were evaluated: brown rice mass (BRM), milling duration (MD), oscillation frequency (OF), and tube head space (THS). Four tube OFs (1740, 1840, 1940, and 2040 r/min) were used. Three tube sizes (12, 16, and 18 mL) were selected based on a preliminary investigation comprising a wide range of tube sizes, from 7 to 20 mL. Parameter values that resulted in a MLP too far from the 12% level were eliminated. Sample masses of 2 to 11 g were selected based on the typical amounts of brown rice produced from a single rice plant (Counce and Wells, 1990). From this preliminary work, brown rice sample masses of 2, 3, 4, and 5 g were used in the 12−mL tube; 5, 6, 7, and 8 g were used in the 16−mL tube; and 9, 10, and 11 g were used in the 18−mL tube. Tube headspace volumes were computed for each tube size containing the corresponding masses of brown rice and aluminum oxide for both cultivars. The following bulk densities were used to calculate the THS volumes: 0.87 g/cc for Bengal brown rice, 0.83 g/cc for Cypress brown rice, and 3.97g/cc for aluminum oxide (Lide, 1997). The brown rice bulk densities represent the average of 10 subsample measurements for each cultivar using the method of Candole et al. (2001). The brown rice bulk densities were similar to bulk densities reported by Bhattacharya et al. (1972). Milling duration was varied from 10 to 25 min as shown in figure 2. The mass of aluminum oxide, with grit size #46 (Duralum special white, Washington Mills Electro Minerals, Inc., Buffalo, N.Y.) was 5 g for all experiments.



12 mL Tube

Oscillation frequency (r/min)	Milling duration (min)
1740	15, 20, 25
1840	15, 20, 25
1940	10, 15, 20
2040	10, 15, 18

16 mL Tube

Oscillation frequency (r/min)	Milling duration (min)
1740	15, 20, 25
1840	15, 20, 25
1940	10, 15, 20
2040	10, 15, 18

18 mL Tube

Oscillation frequency (r/min)	Milling duration (min)
1740	15, 20, 25
1840	15, 20, 25
1940	10, 15, 20
2040	10, 15, 18

Figure 2. Schematic of the experimental design used for evaluating oscillation frequency and milling duration of the IRRI Test Tube mill for milling the indicated brown rice amounts of medium− (Bengal) and long−grain (Cypress) cultivars using three tube sizes. Aluminum oxide (Al_2O_3), grit size #46, was used as a milling aid.

A separate experiment was conducted to determine the amount of aluminum oxide adequate for milling a range of small brown rice samples (cv. Bengal and Cypress) at an OF of 1750 r/min using a 7−mL test tube. The milling parameters of BRM (2, 5, and 8 g), mass of aluminum oxide (2, 3, 4, 5, 6, and 7 g), and MD (20, 30, 40, 50 min) were considered. The MLP, as a function of BRM, aluminum oxide mass, and MD, was adequately represented by a quadratic function (R^2 = 0.76 for Bengal and 0.82 for Cypress) in indicating the effects that aluminum oxide amount had on brown rice MLP. It was found that approximately 5 g of aluminum oxide was sufficient to mill the indicated BRMs described above at an OF of 1750 r/min. Thus, based on this preliminary experiment the amount of aluminum oxide was fixed at 5 g for all experimental treatments.

The response variable used was the MLP, which was computed as follows:

$$\text{BRML (MLP)},\ \% = \frac{\text{MBR} - \text{MMR (head rice and brokens)}}{\text{MBR}} \times 100 \qquad (1)$$

where
BRML = brown rice mass loss;
MBR = mass of brown rice;
MMR = mass of milled rice; and
MLP = mass loss percentage.

Treatment combinations of BRM, MD, OF, and THS were tested for Bengal and Cypress brown rice. All treatment combinations were replicated twice. The experimental procedure consisted of placing the desired masses of brown rice and aluminum oxide in a tube and closing with a stopper. To accommodate 12−, 16−, and 18−mL tubes, pairs of specially designed wooden tube holders were fabricated. Each tube holder had four holes drilled on one face to accommodate a particular tube size; a total of eight tubes were thus available for a given run. Each tube holder was secured on the mill's oscillating arm by a winged lock nut. The OF for each experiment was determined by adjusting the diameter of the variable pulley and checked with a tachometer. A timer was used to monitor the milling duration. After milling, the samples were allowed to cool inside the tubes, opened and separated from the bran and aluminum oxide using a #20 screen (Central Scientific Co., Chicago, Ill.) and weighed.

Whole kernel yield (WKY), which is defined as the ratio of the mass of milled kernels with length at least 3/4 of the original kernel length (head rice) to the mass of rough rice, was measured for each experiment. The mass of rough rice was estimated by dividing the brown rice mass by 80%, since the hulls represent, on average, 20% of the rough rice mass. The head rice may be well milled or could be under−milled, depending on the experimental milling treatment. Whole kernel yield does not represent head rice yield (HRY) of milled rice as used by the commercial milling industry, in that WKY consists of kernels 3/4 or more of the original kernel length that may or may not have been milled to an acceptable degree of milling. To obtain WKY, head rice was separated from brokens by using a sizing machine (Grainman, Model 61−115−60, Grain Machinery Manufacturing Corp., Miami, Fla.). The following equation applies:

$$\text{Whole kernel yield} = \frac{\text{Mass of head rice}}{\text{Estimated mass of rough rice}} \qquad (2)$$

Surface response analyses were performed using a statistical package JMP version 5 (SAS, Inc., Cary, N.C.). The study was conducted from February, 2001 to May, 2001 at the University of Arkansas Rice Processing Laboratories (Fayetteville, Ark.).

Results and Discussion

Mass Loss Percentage Response

Table 1 shows the results of statistical analyses using a surface response technique (JMP ver. 5, SAS 2002). For both rice cultivars, the independent milling parameters BRM, MD, OF, and THS were analyzed for individual and cross parameter effects on MLP. Brown rice mass and THS showed quadratic effects on MLP. Also, the interactive effect of THS*BRM on MLP was significant. Milling duration and OF had linear effects on MLP, wherein MLP increased with increases in MD and OF. This finding confirms earlier results obtained by IRRI (1987a), indicating that MD and OF influence milling performance. For Bengal, the following interactions had significant effects on MLP: OF*BRM,

Table 1. Statistically significant parameter estimates for brown rice mass (BRM, g), milling duration (MD, min), tube oscillation frequency (OF, r/min), and tube head space (THS, %) for predicting mass loss percentage with equations 3 (Bengal) and 4 (Cypress) using the IRRI Test Tube mill, based on the experimental design evaluation indicated in figure 2.

Term[a]	Parameter Estimate Symbols	Estimate	Std. Error	t Ratio	Prob>|t|
Equation 3 (Bengal)					
Intercept	α	−17.94142	2.53893	−7.07	<0.0001
BRM	$\hat{a}_1$	0.09605	0.12611	0.76	0.0447
MD	$\hat{a}_2$	0.19970	0.01713	11.66	<0.0001
OF	$\hat{a}_3$	0.01257	0.00072	17.24	<0.0001
$(BRM)^2$	$\hat{a}_4$	−0.23690	0.10465	−2.26	0.0254
OF*BRM	$\hat{a}_5$	0.00171	0.00071	2.38	0.0189
OF*MD	$\hat{a}_6$	0.00088	0.00024	3.67	0.0004
THS*BRM	$\hat{a}_7$	−0.09941	0.03698	−2.68	0.0082
$(THS)^2$	$\hat{a}_8$	−0.01288	0.00367	−3.51	0.0006
Equation 4 (Cypress)					
Intercept	α	−10.21923	2.54726	−4.01	<0.0001
BRM	$\hat{a}_1$	−0.25742	0.12964	−1.99	0.0494
MD	$\hat{a}_2$	0.23334	0.01639	14.24	<0.0001
OF	$\hat{a}_3$	0.01059	0.00069	15.16	<0.0001
OF*BRM	$\hat{a}_4$	0.00147	0.00081	1.81	0.0062
THS*BRM	$\hat{a}_5$	−0.08554	0.03812	−2.24	0.0267
$(THS)^2$	$\hat{a}_6$	−0.01100	0.00383	−2.87	0.0049

[a] BRM: Brown rice mass (g).
MD: milling duration (min).
OF: tube oscillation frequency (r/min).
THS: tube head space (%) for predicting mass loss percentage with equations 3 (Bengal) and 4 (Cypress) using the IRRI Test Tube mill.

OF*MD, and THS*BRM. For Cypress, only THS*BRM and OF*BRM interactions had significant effects on MLP.

Figures 3 and 4 show the brown rice MLP for the various treatment combinations for Bengal and Cypress, respectively. Bengal generally had lower brown rice MLPs compared to Cypress. These results agree with the findings of Bautista and Siebenmorgen (2002) where a medium−grain Bengal had less bran removed (lower MLP) than a long−grain Drew using the IRRI Test Tube mill. Figures 3 and 4, and table 1, show that a quadratic relationship existed between MLP and the amount of brown rice used in a given tube size for Bengal while for Cypress, a linear relationship was found between MLP and BRM. Mass loss percentage was greatest at various optimum BRM amounts, depending on the tube size, OF and MD. The THS, which is a function of BRM and the tube size, also had a quadratic effect on MLP (table 1, fig. 5) and had interaction effect with BRM in affecting MLP. Figure 5 represents MLP for Cypress for various THS. Data for Bengal is not shown but trends were similar. The THS provides room in which rice kernels can move back and forth and tumble as the tube is shaken by the oscillating motion of the tube holder. Tube head space varies according to rice cultivar, since rice bulk density also varies with the same.

Tube Oscillation Frequency Effect on Mass Loss Percentage

Tube oscillation frequency was found to be critical in milling brown rice using the IRRI Test Tube mill, as MLP increased with increases in tube OF, particularly above 1840 r/min, as shown in figure 6 for Cypress milled for 15 min (data for Bengal is not shown, but trends were similar). For all BRMs, the increase in MLP with OF generally followed a sigmoid pattern with the most dramatic increases in MLP occurring between OFs of 1840 and 1940 r/min. The relationship between MLP and tube OF can be explained by the fact that abrasion of rice kernels is increased with an increase in the frequency of the kernel movement against both the abrasive compound and other kernels.

Milling Duration Effect on Mass Loss Percentage

Mass loss percentage was directly and linearly affected by MD. The interaction of MD and OF was also found to significantly affect MLP for Bengal (table 1). For a given BRM, MLP increased with an increase in MD at any OF as shown in figures 3 and 4 for Bengal and Cypress, respectively. Mass loss percentage for Bengal was lower than Cypress, particularly for shorter milling durations (10 and 15 min). A desirable MLP of 12% was attained in 10− to 25−min MD for both varieties using different BRMs, depending on treatment combinations of OF and tube size. These MDs were shorter than the results earlier reported by Bautista and Siebenmorgen (2002) on the IRRI mill. In the 2002 report, 120 min was required to mill a long grain (Drew at 12% MC) and 180 min for a medium grain (Bengal at 12% MC). Bautista and Siebenmorgen (2002) used an OF of 1580 r/min and a THS of 69.2%; both of these parameters are shown to be critical in affecting MLP. The values of these parameters used by Bautista and Siebenmorgen (2002) were different (much lower OF and higher THS) than those parameters used in the current study, explaining much of the difference in MD between the two studies.

Whole Kernel Yields

The trend in WKY with MD was the opposite of MLP (figs. 6 and 7). Figures 7 and 8 show the WKYs obtained in milling different masses of Bengal and Cypress brown rice using different milling treatment combinations. Whole kernel yield was inversely related to MD wherein WKY decreased with increases in MD. For different tube sizes and sample masses, the trend in WKY was similar across all OFs. Between cultivars, Bengal had, in most cases, lower WKYs than Cypress.

Parameter Design Estimates for Optimum Milling Using the IRRI Test Tube Mill

A strategy to set up a milling procedure to determine the most effective setting of the IRRI mill to obtain a 12% MLP is proposed. From table 1, the regression models for Bengal (R^2= 0.756) and Cypress (R^2= 0.762) using the IRRI Test Tube mill using variables with significant effects on MLP are shown as equations 3 and 4:

$$MLP_{Bengal} = \alpha + \beta_1(BRM) + \beta_2(MD) + \beta_3(OF) + \beta_4(BRM)^2 + \beta_5(OF*BRM) + \beta_6(OF*MD) + \beta_7(THS*BRM) + \beta_8(THS)^2 \quad (3)$$

$$MLP_{Cypress} = \alpha + \beta_1(BRM) + \beta_2(MD) + \beta_3(OF) + \beta_4(OF*BRM) + \beta_5(THS*BRM) + \beta_6(THS)^2 \quad (4)$$

where

α = intercept

β_i = parameter estimates

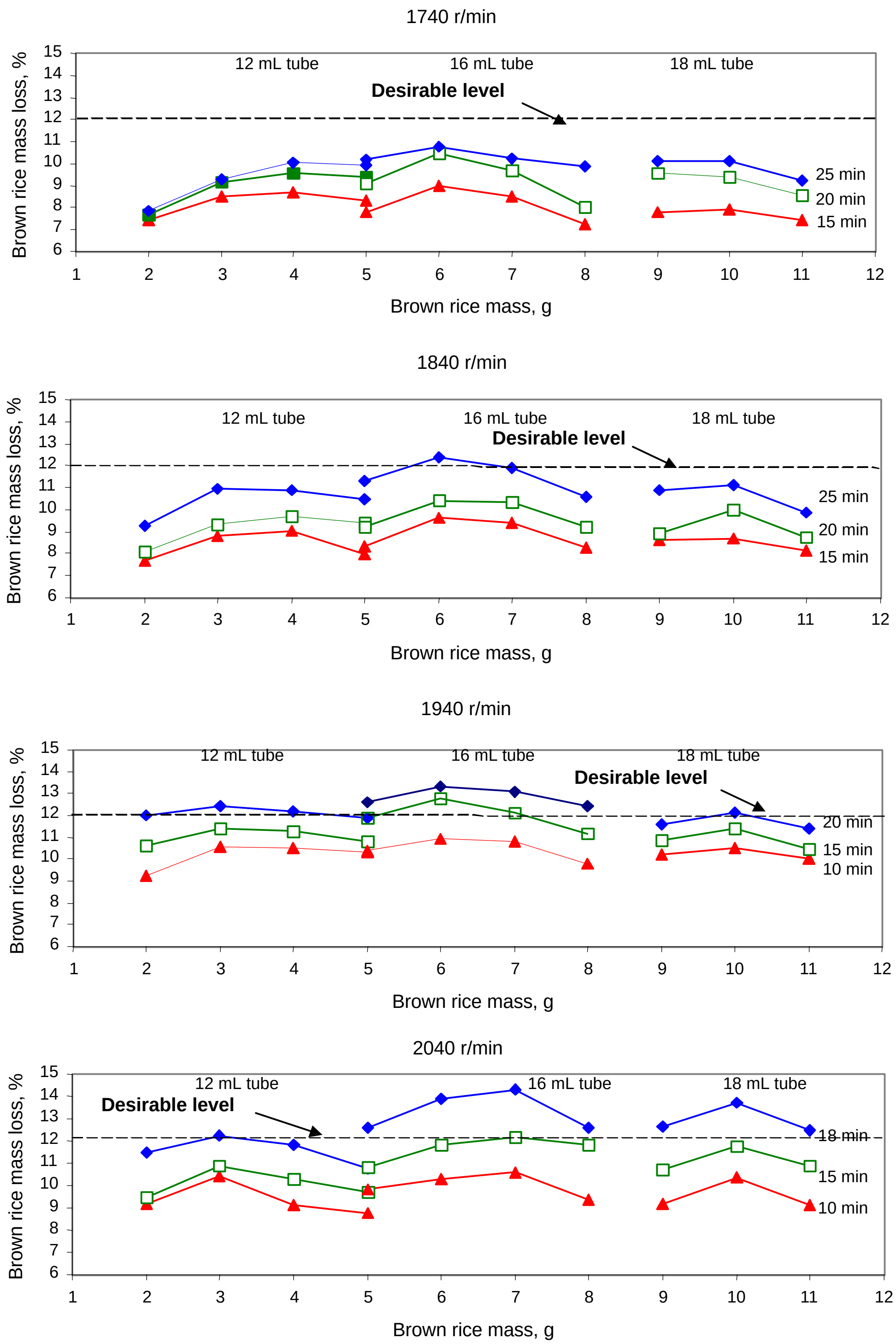


Figure 3. Brown rice mass loss percentages for Bengal brown rice (at 12.5% MC) milled with the IRRI Test Tube mill using oscillation frequencies of 1740, 1840, 1940, and 2040 r/min, at various milling durations, brown rice masses, and tube sizes. A desirable milling level equivalent to 12% mass loss percentage of brown rice is indicated. Each data point is the average of two replications.

Parameter estimate values are given in table 1 for Bengal and Cypress, respectively.

These empirical equations are the result for Bengal and Cypress. In milling other varieties under different conditions, the rice moisture content, as well as other milling factors such as the extent of aging, must be considered to attain a certain MLP. Findings of Andrews et al. (1992) suggest that MD required to remove bran varies with rice variety and MC; Daniels et al. (1998) showed that MD required to achieve a certain DOM varies with the storage duration and condition.

In using equations 3 and 4, the value of an independent parameter can be estimated with three other known independent variables to obtain a desirable MLP of 12%. For example, MD can be predicted for a known MBR, THS, and OF to attain a 12% MLP. These results can also be used in designing a mill with similar applications.

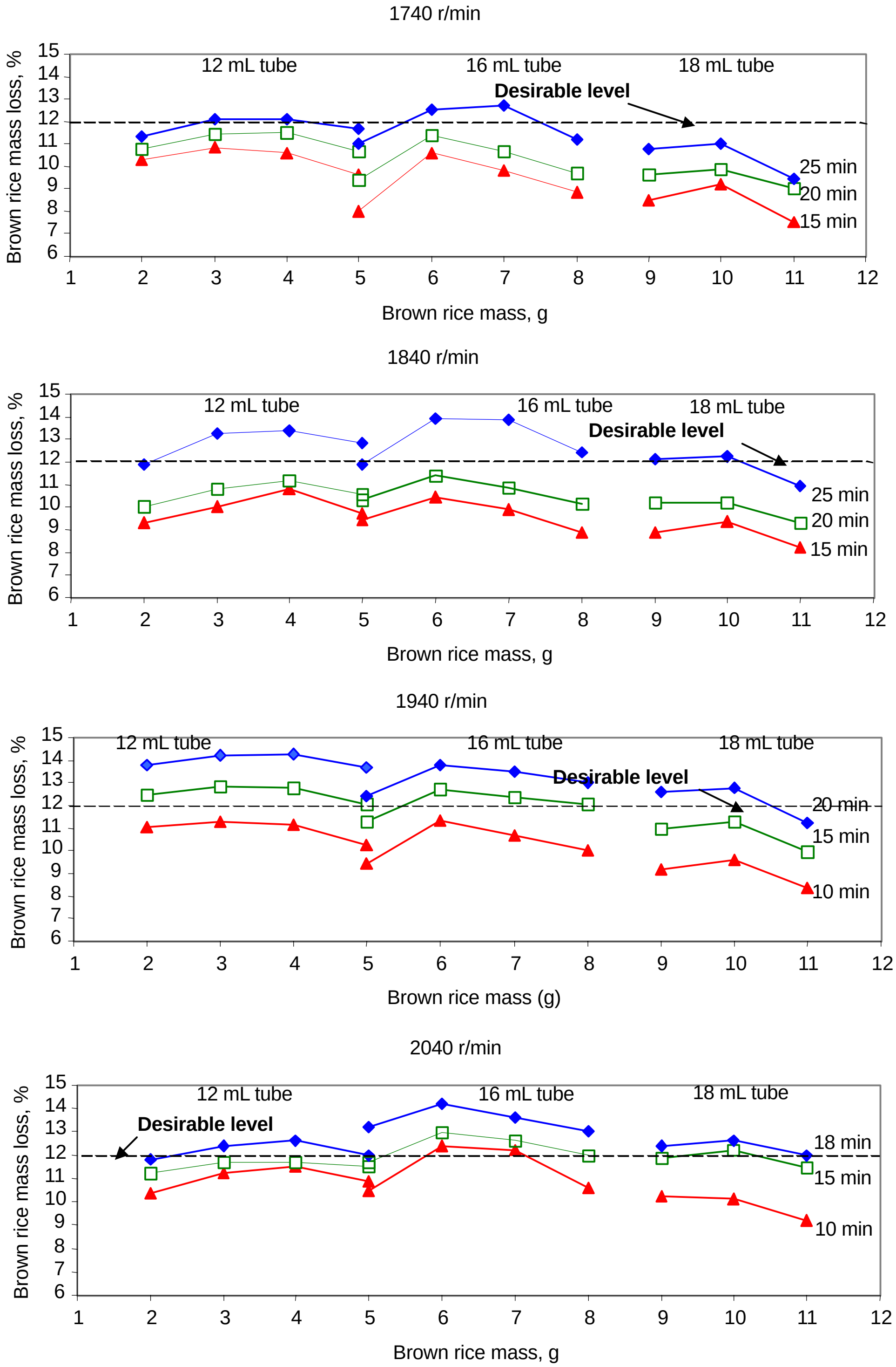


Figure 4. Brown rice mass loss percentages for Cypress brown rice (at 12.1% MC) milled with the IRRI Test Tube mill using oscillation frequencies of 1740, 1840, 1940, and 2040 r/min, at various milling durations, brown rice masses, and tube sizes. A desirable milling level equivalent to 12% mass loss percentage of brown rice is indicated. Each data point is the average of two replications.

Conclusions

This study determined the effects of milling parameters on MLP for the IRRI Test Tube mill. Among the independent variables, BRM, MD, OF, and THS had statistically significant impacts on the MLP. Regression models were determined to predict the effect of the various experimental variables on MLP. These equations can be used to predict the MD, given values of MBR, THS, and OF, required to attain various MLPs. A desirable MLP level of 12% was attained at 10 to 25 min, depending on the parameter combination. The results of this study would be useful in operating laboratory mills with similar milling characteristics as the IRRI mill.

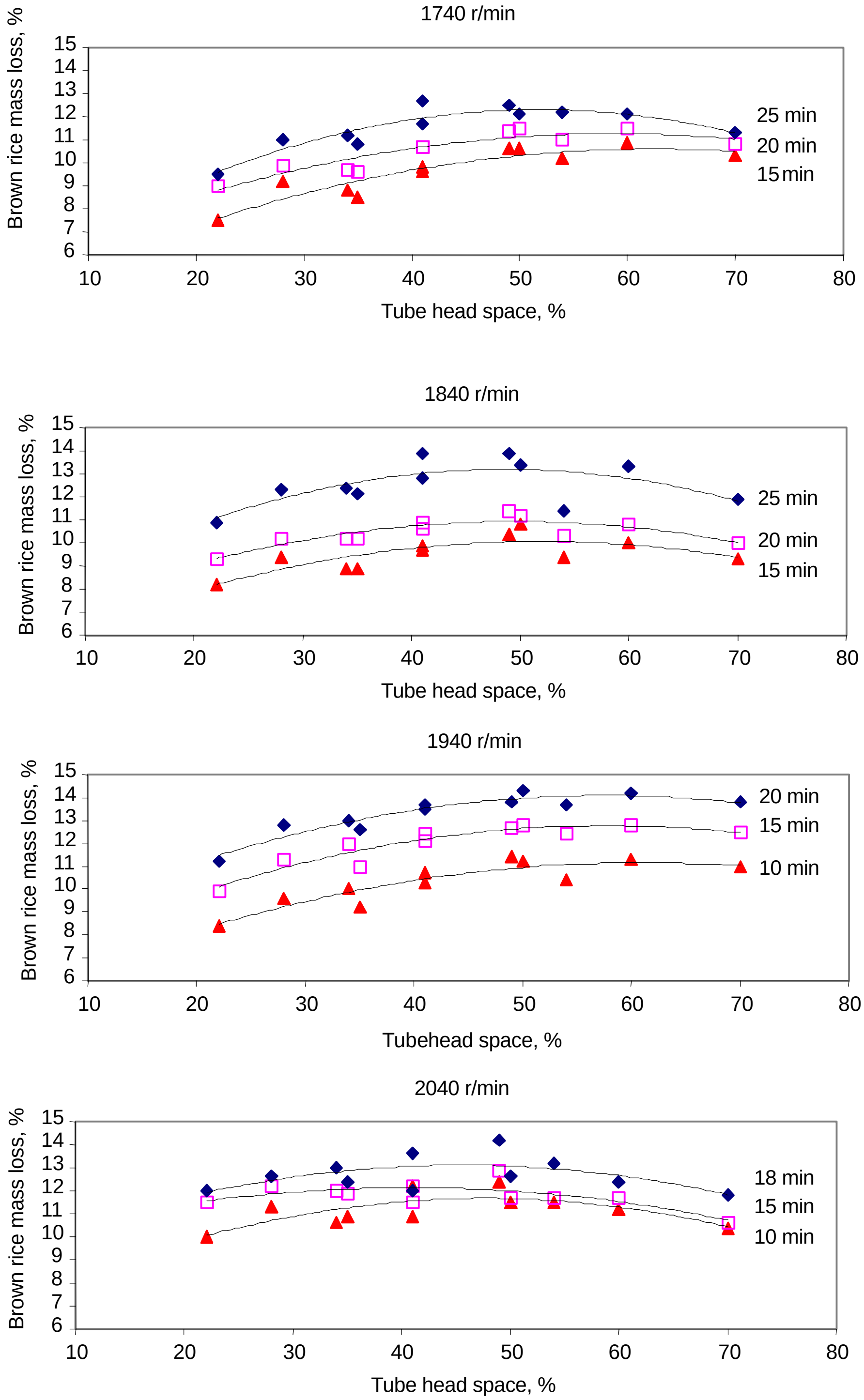


Figure 5. Test tube head space and corresponding brown rice mass loss percentages for Cypress brown rice (at 12.1% MC) milled with the IRRI Test Tube mill using oscillation frequencies of 1740, 1840, 1940, and 2040 r/min at various milling durations.

Acknowledgements

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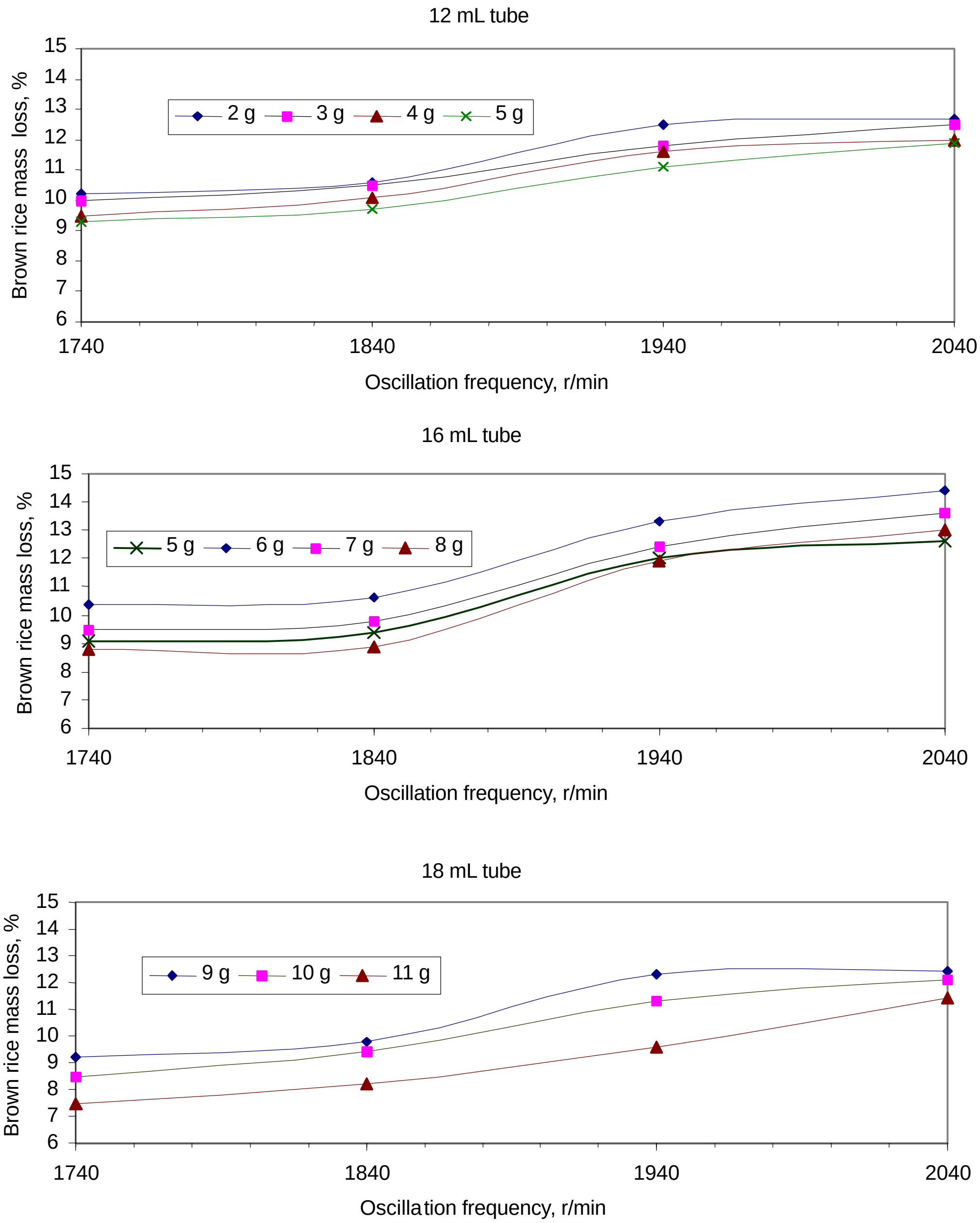

Figure 6. Mass loss percentages obtained for different masses of Cypress brown rice when milled for 15 min at various tube oscillation frequencies in a 12−, 16−, and 18−mL tube using the IRRI Test Tube mill. Each data point represents the average of two replications.

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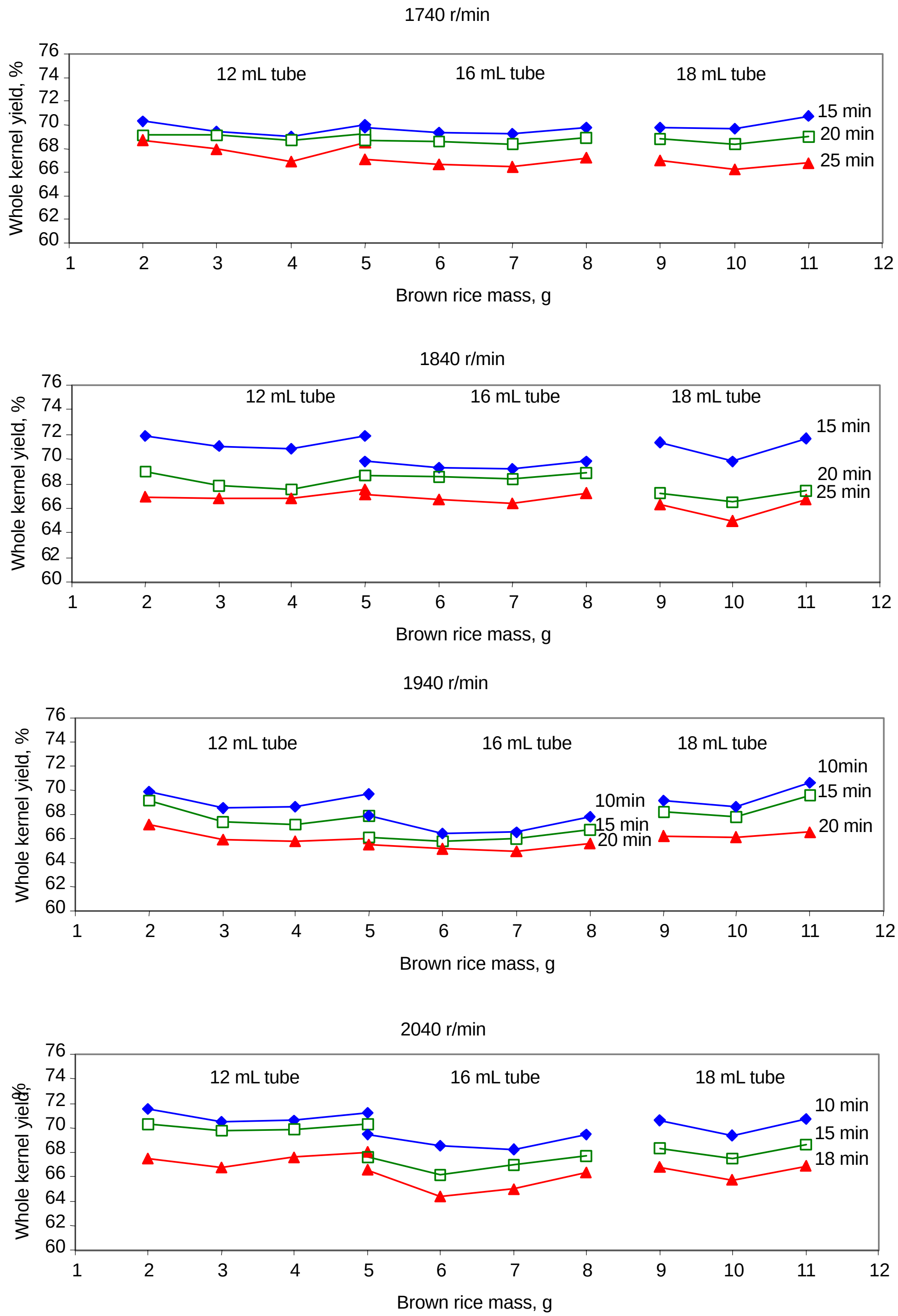

Figure 7. Whole kernel yields (eq. 2) obtained for Bengal in milling the indicated amounts of brown rice at different tube oscillation frequencies and milling durations using the IRRI Test Tube mill. Each data point represents the average of two replications.

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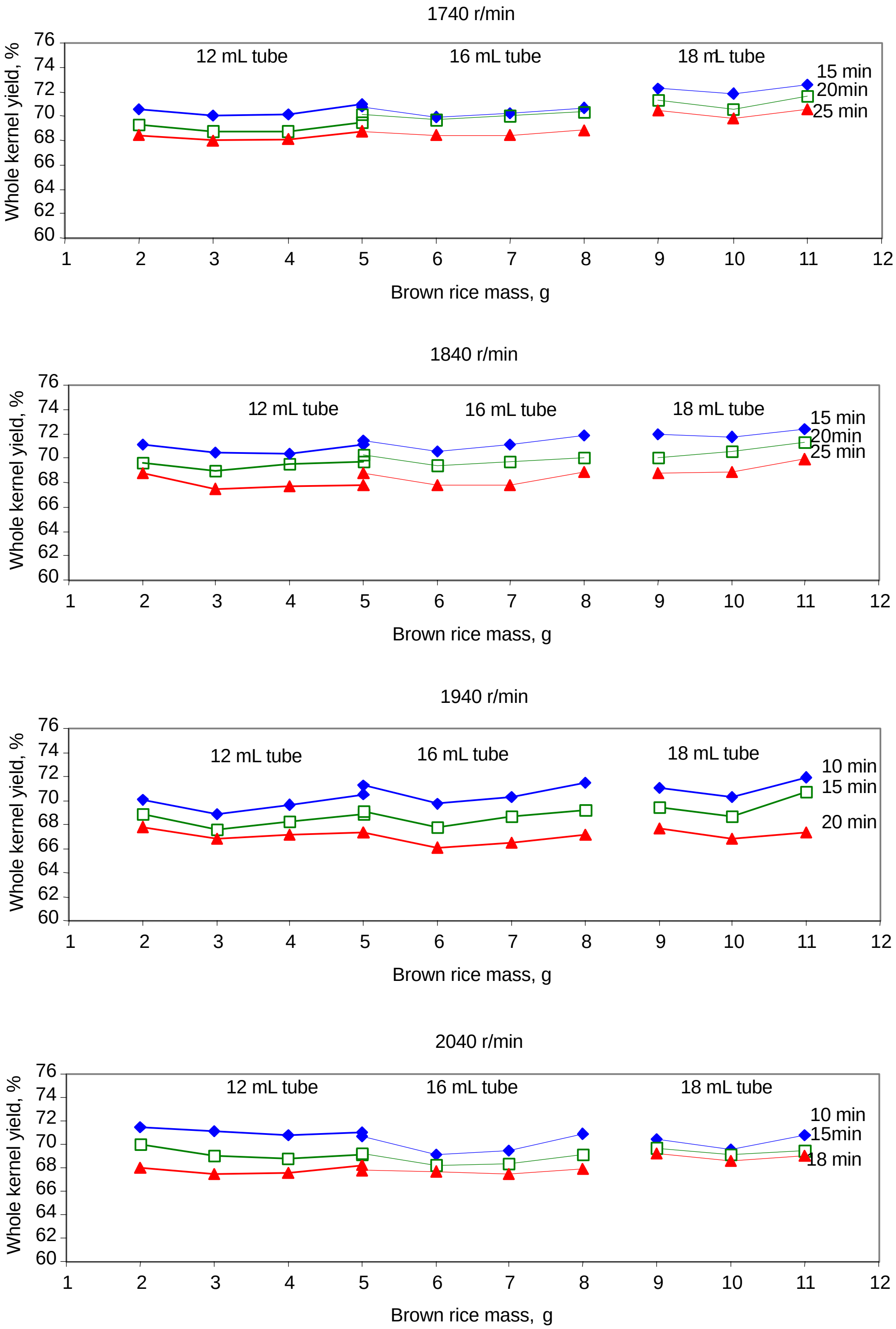

Figure 8. Whole kernel yields (eq. 2) obtained for Cypress in milling the indicated amounts of brown rice at different tube oscillation frequencies and milling durations using the IRRI Test Tube mill. Each data point represents the average of two replications.

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