A Review of Hygroscopic Equilibrium Studies Applied to Rice

B.-M. Choi, S. B. Lanning, T. J. Siebenmorgen

Abstract. *Equilibrium moisture content (EMC)/equilibrium relative humidity (ERH) studies pertaining to rice and rice products were reviewed. Methods of determining rice and rice component EMC/ERH data varied, using procedures involving static and dynamic equilibration methods, as well as direct gravimetric methods and indirect ERH-measurement methods. Methods for measuring rice and rice component moisture contents also varied. The Modified Henderson and Modified Chung-Pfost equations were most frequently recommended for predicting the sorption behavior of rice. Among rough rice components, for any given temperature and relative humidity, the EMC of milled and brown rice were consistently the greatest, generally followed by rough rice, bran, and hull. The hysteresis effect was apparent in rice. The magnitude of hysteresis decreased with repeated cycles of drying and rewetting and with increasing temperature. EMC/ERH relationships were affected by rice cultivar, but harvest location was not a significant factor. As such, in order to be most accurate, EMC/ERH equations for each rice cultivar need to be determined.*

Keywords. *Equilibrium moisture content, Equilibrium relative humidity, Hygroscopic equilibria, Isotherm, Rice.*

Rice is harvested as rough, or paddy, rice at moisture contents (MCs) greater than the generally accepted level of 12% to 13% considered safe for long-term storage (all moisture contents are expressed on a wet basis unless otherwise noted). It is thus dried before storage and subsequent processing. Brown rice is produced by removing the hulls and is sometimes referred to as husked rice or hulled rice in various parts of the world. During milling, the bran layers and embryo are removed from the brown rice kernel, producing milled rice, also known as white or polished rice. Typically, head rice, milled kernels with length three-fourths or more of the original kernel length (USDA, 2005), is separated from broken kernels. Head rice yield (HRY) is the mass ratio of head rice to rough rice (USDA, 2005). The moisture content of rough rice or of any of the processing fractions plays a determining role in storage, milling, and end-use processing performance.

Since rice, like other cereal grains, is a composite of hygroscopic materials, it will lose or gain moisture in any environment with which it is not at equilibrium. This transfer, and the rate of transfer, is determined by the moisture gradient between kernels and the interstitial air; a kernel will gain or lose moisture when the vapor pressure of water in the space surrounding the kernel is greater or less, respectively, than the vapor pressure exerted by the moisture within the kernel (Kachru and Matthes, 1976). Equilibrium moisture content (EMC) is defined as the MC of a hygroscopic material in moisture equilibrium with air of a given relative humidity (RH) and temperature (Coleman and Fellows, 1925; Henderson, 1952; Kachru and Matthes, 1976; Kunze, 1979; Yu and Wang, 2006). The EMC of a material, such as rice, usually decreases with increasing temperature at constant RH and increases with increasing RH at constant temperature (Brockington et al., 1949; Chen, 2000).

The importance of EMC data has long been recognized for achieving conditions during drying, storage, and processing that are necessary for optimum quality. In drying processes, the EMC represents the limiting MC that can be reached under a given drying air temperature and RH. The EMC also affects the rate of moisture transfer from kernels to the surrounding air, which can affect rice milling quality (Fan et al., 2000; Kunze, 1979). In storage, EMC data are used to determine if grain mass will increase or decrease when aerated with air at given conditions.

Across materials, Neuber (1980) lists the following factors as sources of variation in EMC/equilibrium relative humidity (ERH) data: (1) material characteristics (variety, growth environment, and particle size); (2) composition of material (ash, oil or fat, fiber, protein, starch, and sugar); (3) pretreatment of samples (air drying temperature and RH, drying duration, drying method, and rewetting method); (4) method for measuring MC and RH (direct or indirect); (5) method of equilibration (static or dynamic); and (6) method of controlling the air temperature and RH during the experiment. The following sections comprise a review of EMC/ERH research directed to rice and rice components, in which many of these factors are addressed.

Measurement of Hygroscopic Equilibrium

EMC/ERH properties have been measured directly or indirectly by a number of methods. A sample may be placed in

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an environment maintained at a constant temperature and RH, either via chemical means, as with saturated salt solutions, or through mechanical means, as with vapor compression refrigeration systems. The sample will gain or lose moisture until, after an extended period, it reaches hygroscopic equilibrium with the environment, identified as the point at which the sample reaches a constant mass (Fan et al., 2000). The EMC of the sample is then measured, typically gravimetrically. This process may be considered a direct approach to obtaining EMC data. Alternately, a sample of known MC may be placed in a limited volume, and the ERH may be determined by measuring the air conditions (usually temperature and RH or dew point temperature) of the volume by some psychrometric method, such as an electronic hygrometer (Brockington et al., 1949; Hogan and Karon, 1955; Pixton and Warburton, 1971, 1975; Putranon et al., 1979). This method, considered herein as an indirect approach, can shorten the duration required for obtaining EMC/ERH data (Chen and Morey, 1989b) and is essentially the principle used by commercial water activity meters.

Whether measured directly or indirectly, a sample's hygroscopic equilibrium may be attained by static or dynamic approaches. In the static approach, a sample reaches its equilibrium state in still air. With a dynamic approach, the air surrounding the sample is mechanically circulated. In relation to commercial applications, the dynamic approach is more representative of drying conditions, while the static approach is more appropriate for simulating storage situations (McEwen et al., 1954). While the static method offers the advantage that environmental air conditions can be maintained more easily, the dynamic method purportedly allows samples to reach equilibrium more quickly (Basunia and Abe, 2001; Juliano, 1964; Nilsson et al., 2005). Despite the dynamic method's advantage of shortened exposure duration, it is known that conditioning of air at low temperature and high RH is somewhat difficult to achieve. Banaszek and Siebenmorgen (1990) reported that air conditions of 12.5°C/50% RH, 15°C/50% RH, and 12.5°C/90% RH were not obtainable with the RH and temperature control unit used for their adsorption EMC experiment with rough rice. Table 1 summarizes experimental methods that have been used to measure rice hygroscopic equilibria data.

Table 1. Methods used to measure equilibrium moisture content (EMC)/equilibrium relative humidity (ERH) of rice.

		Measurement Method		
	Reference	Static	Dynamic	Remarks
Direct Methods (equilibrium determined by change of product MC)	Coleman and Fellows (1925)	x		Sulfuric acid solution
	Rao (1939, 1945)	x		Charcoal, silica gel, Gatton stone, ferric oxide, platinum
	Karon and Adams (1949)	x		Salt solution
	Houston (1952)	x		Salt solution
	Houston and Kester (1954)	x		Salt solution
	Breese (1955)	x		Sulfuric acid solution
	Rangaswamy (1973)	x		Salt solution
	Zuritz et al. (1979)	x		Salt solution
	Aguerre et al. (1983)	x		Salt solution
	Chen et al. (1984)	x		Salt solution
	Kameoka et al. (1986)	x		Salt solution
	Gencturk et al. (1986)	x		Salt solution
	Chang (1987)	x		Salt solution
	Fan et al. (2000)	x		Salt solution
	Keum et al. (2000)	x		Salt solution
	San Martin et al. (2001)	x		Sulfuric acid solution
	Reddy and Chakraverty (2004)	x		Salt solution
	Yu and Wang (2006)	x		Salt solution
	Goneli et al. (2007)	x		Salt solution
	Iguaz and Virseda (2007)	x		Sulfuric acid solution
	Juliano (1964)		x	Salt solution with air blow
	Kachru and Matthes (1976)		x	Thin-layer drying
	Banaszek and Siebenmorgen (1990)		x	Aerated conditioning chamber
	Lu and Siebenmorgen (1992)		x	Air conditioning chamber
	Jindal and Siebenmorgen (1994)		x	Air conditioning chamber
	Basunia and Abe (1999)		x	Thin-layer drying
	Basunia and Abe (2001)		x	Thin-layer drying
	Haque et al. (2007)		x	Salt solution with circulating air
Indirect Methods (equilibrium determined by change of surrounding air RH)	Putranon et al. (1979)	x		ERH method by relative humidity sensor
	Benado and Rizvi (1985)	x		Water activity by capacitance manometer
	Chung and Verma (1991)	x		ERH method by relative humidity sensor
	Chen (2000)	x		ERH method by relative humidity sensor
	Choi (2005)	x		ERH method by relative humidity sensor
	Hogan and Karon (1955)		x	Humidity meter with air blower
	Henderson (1970)		x	Dew point hygrometer with air pump
	Pixton and Warburton (1975)		x	Dew point method

Sample Preparation Techniques for Rough Rice and Its Fractions

Most researchers have elected to investigate EMCs attained through both adsorption (moisture gain) and desorption (moisture loss). In preparation for adsorption, Breese (1955) dried rough rice samples in a ventilated oven to a MC of 5.8% and then further dried them in a vacuum oven to a MC of 3.3% at temperatures not exceeding 70°C. Samples prepared for desorption were stored for more than four months in a 90% RH environment. Juliano (1964), in preparation for desorption, soaked rough rice samples for 10 min in distilled water and kept the samples in a humidity chamber with a saturated potassium sulfate solution at an equilibrium relative humidity of 96.5%. After completing the desorption isotherms, the samples were dried with anhydrous calcium sulfate to a MC of about 5% to prepare for adsorption. Putranon et al. (1979) prepared rough rice by adding distilled water to allow the MC to increase to about 22% for desorption isotherm determinations. Samples to be used in adsorption experiments were prepared by drying paddy in a 40°C oven to about 7% MC and then subdividing the dried paddy and adding distilled water to produce the desired MCs. Aguerre et al. (1983) dried rough rice to a MC of about 13% dry basis (d.b.) in the field and then conditioned the rice for one month using a RH of 95% by placing the kernels in thin layers on trays. The samples were subsequently stored at 4°C to equilibrate, with the final MC of the rough rice taken as the initial MC for the determination of desorption isotherms. San Martin et al. (2001) dried rough rice at 70°C and a pressure of less than 100 mm Hg in preparation for an adsorption study. Yu and Wang (2006) dried samples in a 50°C oven until maximum dehydration had been reached for adsorption experiments. Choi (2005) prepared for adsorption and desorption experiments by adding distilled water to rough rice and brown rice samples. For adsorption testing, the samples were first dried at 45°C to 8% MC (d.b.) and then rewetted with distilled water to reach desired MCs.

Pixton and Warburton (1975) prepared rice bran samples for adsorption tests by conditioning the samples in dessicators at 22% RH and 25°C for nine to ten weeks. For desorption testing, bran samples were wetted with an atomized spray of distilled water and left to equilibrate at 5°C for 14 days. Reddy and Chakraverty (2004) prepared samples of raw and parboiled paddy, brown rice, and bran for adsorption studies by first drying the samples to 5% to 7% (d.b.) MC in an air oven at 50°C.

Benado and Rizvi (1985) dehydrated samples of ground polished rice by heating to 65°C for 6 h in a vacuum oven for subsequent adsorption isotherm measurements. Fan et al. (2000) dried rough rice to approximately 12.5% MC for one week using a chamber held at 21°C and 50% RH. After milling, the samples were placed in different temperature/RH environments maintained by saturated salt solutions and allowed to equilibrate in order to study milled rice EMC.

Banaszek and Siebenmorgen (1990) studied the effect of initial MC of rough rice dried to approximately 9.0%, 10.5%, 12.0%, 13.5%, and 15% on subsequent adsorption EMCs, reporting that EMC varied directly and linearly with initial MC. A difference of one percentage point was observed between the EMCs of rice samples, initially at MCs of 9% and 15.5%, after being equilibrated to an air condition of 30°C and 90% RH. The study concluded that a correlation existed between initial MC and EMC at all of the adsorptive air conditions tested, suggesting an extension of the hysteresis theory, in that EMC differences depend not only on whether equilibrium has been reached through adsorption or desorption but also on initial MC, at least with respect to adsorption. However, Basunia and Abe (2001) reported that rough rice EMCs measured at 19.7°C and 88% RH were similar when drying from varying initial MCs of 24.7%, 28.3%, 32.1%, and 41.6% (d.b.), attained by artificially moistening the samples prior to drying.

Chen (2000) dried rough rice and brown rice at 25°C and 50°C to observe the effect of drying temperature on ERH. In preparation for the adsorption treatments, samples were either conditioned in a low-RH environment produced by a saturated salt solution or dried by heated air to a base MC of 3% to 4% (d.b.) and then rewetted by water spray to reach a desired MC. The author reported that the drying temperature used for sample preparation had a significant effect on isotherm curves; increased drying temperatures significantly reduced water holding ability. For example, in desorption studies, the EMCs of rough rice samples that had been dried at 50°C were approximately two percentage points less than those dried at 25°C across an ERH range of 40% to 80%. Karon and Adams (1949) measured EMCs of rough rice and its fractions (head rice, bran, hulls and waste), using artificially dried rice (dried in a commercial drier at an unspecified temperature) and naturally dried rice (details of the natural-drying technique not given) with MCs of 17.8% and 16.8%, respectively. There were only small differences between the corresponding equilibrium values of naturally and artificially dried rice components. In those cases where the difference in EMC at a given air condition was significant, the artificially dried sample produced a lesser MC.

Methods Used and Durations Required to Attain Hygroscopic Equilibrium

Conditions used to achieve moisture equilibrium between kernels and surrounding air vary with research objectives and techniques. For example, Lu and Siebenmorgen (1992) and Lan and Kunze (1996) both studied moisture adsorption rates, but the former used a temperature- and RH-controlled chamber to reach ERH, while the latter used saturated salt solutions to generate the required air conditions.

Table 1 indicates that most rice EMC/ERH studies have used a static-air approach to attain equilibrium. In most of these experiments, a small sample of material was placed in a sealed container with a saturated salt or sulfuric acid solution of a specific concentration in order to produce a certain water vapor pressure or RH. Using this approach, the normal duration required for a rice sample to reach equilibrium with its environment ranged from days to months. Karon and Adams (1949) investigatedthe rate of moisture sorption and desorption by rough rice, head rice, bran, polished rice, and hulls over a range of 11% to 93% RH at 25°C. They reported that the samples attained hygroscopic equilibrium within a period of three weeks, with the exception of those equilibrated over solutions producing very high RHs, which took approximately 30 days. Breese (1955) observed that equilibration required 56 days for rough rice exposed to air at 25°C and RH from 10% to 90%. Fan et al. (2000) reported that rough rice samples typically reached a constant mass after equilibration for approximately four weeks at temperatures of 4°C, 21°C, and 38°C with RH ranging from 11% to 96%. Keum et al. (2000) determined desorption EMCs of rough rice, brown rice, white rice, and rice hulls grown in Korea at three temperature levels (20°C, 30°C, and 40°C) and eight RH levels ranging from 11.2% to 85.0%. The study reported that all samples attained hygroscopic equilibrium within a period of 7 to 14 weeks. Kameoka et al. (1986) determined desorption EMCs of rough rice, brown rice, and rice hulls under similar conditions and reported that the samples took at least 55 days to attain equilibrium in the surrounding atmosphere, but that this duration could be shortened by incorporating a small fan to circulate the air.

Because of the long exposure period required under static air conditions, samples at approximately 85% RH or greater tend to mold before equilibrium can be reached (Breese, 1955; Houston, 1952; Zuritz et al., 1979). To avoid spoilage due to mold growth, Zuritz et al. (1979) applied a 2% weight mixture of 40% propionic acid and 60% acetic acid with 2% by weight of sodium benzoate to rice samples. Fan et al. (2000) placed toluene in the EMC container when testing RHs of 75% or greater. Juliano (1964) applied a dynamic approach in attaining EMCs of rough rice, using a centrifugal fan to continuously circulate air above a salt solution and over the surface of samples. The author reported that final MCs of rice were attained within 2 to 4 days, thus preventing mold growth in humid atmospheres.

Work has also been done to determine desorption and adsorption EMCs of rough rice under aerated, dynamic conditions. Some researchers have used chambers with self-contained air conditioning units to maintain desired air temperatures and RHs for attaining equilibrium conditions (Bausunia and Abe, 1999, 2001; Jindal and Siebenmorgen, 1994).

Banaszek and Siebenmorgen (1990) studied the EMC of rough rice at initial MCs of 9% to 15%, exposing each to moisture adsorbing conditions from an airstream at temperatures between 12.5°C and 30°C and RHs between 70% and 90%. Equilibrium conditions were reached within 168 h. Kachru and Matthes (1976) conducted sorption experiments using a thin-layer drying unit for rough rice at 526°R, 540°R, 550°R, 560°R, and 568°R (approx. 19°C, 27°C, 32°C, 38°C, and 42°C, respectively) over a RH range of 5% to 90% and reported that it took 24 to 60 h for the samples to reach equilibrium. Lu and Siebenmorgen (1992) conducted adsorption tests for rough rice at temperatures ranging from 12°C to 50°C in a conditioning chamber with air supplied by a temperature and RH control unit. They reported that white and brown rice reached equilibrium within 24 h for all test conditions. However, after 72 h of exposure to the conditioned air at temperatures below 25°C, rough rice still had not reached equilibrium. Other researchers (Kachru and Matthes, 1976) have used similar dynamic approaches.

Several researchers collected ERH data using temperature and RH sensors (Chen and Morey, 1989b; Choi, 2005; Chung and Verma, 1991; Putranon et al., 1979). With this approach, samples in airtight containers were placed in a temperature-controlled chamber. The dry-bulb temperature and the RH of the air within the containers were measured. After equilibrium had been reached at a given temperature, the chamber was adjusted to the next level of temperature. Moving the chamber through a series of temperatures with a series of known MC samples enabled a large amount of ERH data to be collected over a short time period (4 to 24 h per temperature setting).

Hogan and Karon (1955) used a dynamic method for measuring ERH of rough rice. In this procedure, rice was sealed in a chamber that permitted circulation of air through the rice. During the procedure, the chamber was subjected to a constant-temperature water bath. The chamber was filled with 8 to 9 lb_m of rice of a predetermined MC and sealed by securely fastening the outlet plate and inlet flange of the blower. The air blower was operated at a speed sufficient to ensure rapid circulation of the air through the rice bed. Approximately 5 h were required to reach equilibrium for measurement of ERH at a given temperature. After each run, the water bath temperature was increased and the experiment was repeated.

Moisture Content Determination

Accurate measurement of rice MC is critical when collecting EMC/ERH data. ASABE Standard S352.2 (*ASABE Standards*, 2008) provides specifications, including required drying durations at set temperatures, for measuring the MC of many unground grains and seeds using some type of oven. However, there is no established standard for measuring the MC of rice or rice components. Table 2 summarizes the oven methods that have been used to measure MC in rice EMC studies. This summary shows that the methods of determining dry mass of rice using an air oven encompass a wide range of drying temperatures and durations, varying from 100°C to 135°C with corresponding durations of 120 to 16 h.

In a study unrelated to EMC/ERH determination, Jindal and Siebenmorgen (1987) tested a range of air conditions and drying durations for determining the MC of whole-kernel rough rice in an air convection oven, compared to MCs attained with a standard AOAC air oven method (130°C, 1 h, ground sample). The results showed that the oven drying duration for MC determination of unground rough rice depended upon the initial MC of the sample; low-MC samples required shorter drying durations than high-MC samples. A drying duration of 11.5 h at 130°C was satisfactory for general use in the MC range of 9% to 22%.

Little information was found regarding the MC determination of rice kernel fractions or rice products. Many researchers (Choi, 2005; Fan et al., 2000; Karon and Adams, 1949; Lu and Siebenmorgen, 1992; Keum et al., 2000; Reddy and Chakraverty, 2004) determined MC of rice components with the same MC determination method used for rough rice samples. Houston and Kester (1954) ground parboiled rice and quick-cooking rice samples before drying for 5 h at 100°C in a vacuum oven. Pixton and Warburton (1975) determined the MC of rice bran by drying at 103°C to a constant sample mass. Haque et al. (2007) determined MC of rice kernels in various forms (rough, brown, and milled) using an ISO standard method for rice, wherein approximately 5 g of ground sample were dried at 130°C for 2 h in an air oven. Benado and Rizvi (1985) determined MC of ground rice using an active oven method, and Houston (1952) determined MC of brown rice by a vacuum oven method.

EMC/ERH Equations

Numerous studies have collected and subsequently modeled EMC/ERH data for rice and rice components. Sorption isotherms, representing the relationship between the EMC of a material, such as rice, and the ERH of the surrounding air at a given temperature, are typically described by some type

Table 2. Methods and specifications used for moisture content determination of rice and rice products in equilibrium moisture content studies.

Reference	Form or Product	Method Cited[a]	Temp. (°C)	Duration (h)	Oven Type	Mass (g)	Sample Processing	Remarks
Aguerre et al. (1983)	Rough rice	--	70	96	Vacuum oven	--	--	Used magnesium perchlorate as dessicant
Basunia and Abe (1999)	Rough rice	JSAM (1984)	135	24	Air oven	--	Whole	
Basunia and Abe (2001)	Rough rice	JSAM (1984)	135	24	Forced-air oven	--	Whole	
Benado and Rizvi (1985)	Milled rice	AOAC (1978)	--	--	--	--	Ground	
Breese (1955)	Rough rice	--	130	1	Mechanical convection oven	--	Ground	Preconditioning for 18 to 40 h
Chang (1987)	Rough rice	--	105	24	--	3-5	Whole	
Choi (2005)	Rough rice, brown rice	--	135	24	Air oven	--	Whole	
Chung and Verma (1991)	Rough rice	--	110	24	--	--	--	
Coleman and Fellows (1925)	Rice	--	100	120	Water oven	--	--	
Fan et al. (2000)	Rough rice, milled rice	ASAE (1998) for cereal grain	130	24	Convection oven	10-15	--	
Gencturk et al. (1986)	Wild rice	--	130	72	Air oven	--	--	
Goneli et al. (2007)	Rough rice	--	105	24	Air oven	--	--	
Haque et al. (2007)	Rough rice, brown rice, milled rice	ISO R712 (1979)	130	2	Air oven	5	Ground	
Henderson (1970)	Rough rice	Standard two-stage	--	--	Air oven	--	--	
Houston (1952)	Brown rice	AOAC (1950)	--	--	Vacuum oven	--	--	
Houston and Kester (1954)	Parboiled rice, quick-cooking rice	AOAC (1950)	100	5	Vacuum oven	--	Ground	
Iguaz and Virseda (2007)	Rough rice	AOAC (1996)	70	18	Vacuum oven	--	--	
Juliano (1964)	Rough rice	AOAC (1960)	--	--	Vacuum oven	--	--	
Kachru and Matthes (1976)	Rough rice	--	105	24	Forced convection oven	5-8	--	
Karon and Adams (1949)	Rough rice, head rice, polished rice, bran, hull	--	101	16	Forced-air oven	--	--	
Keum et al. (2000)	Rough rice, brown rice, white rice, hull	--	135	24	Air oven	--	--	
Lu and Siebenmorgen (1992)	Rough rice, brown rice, white rice	--	130	24	Air oven	--	--	
Pixton and Warburton (1975)	Bran	BSI method for oilseeds	103	--	Natural ventilation oven	--	--	Dry until constant weight
Putranon et al. (1979)	Rough rice	AACC (1962)	--	--	--	--	--	
Rangaswamy (1973)	Rice	--	105	24	Air oven	--	--	
Reddy and Chakraverty (2004)	Paddy (raw and parboiled), brown rice, bran	--	104	24	Ventilated oven	--	--	
Yu and Wang (2006)	Rough rice	--	105	--	--	--	--	Dry until constant weight
Zuritz et al. (1979)	Rough rice	--	100	120	Standard oven	--	--	

[a] JSAM = Japanese Society of Agricultural Machinery, AOAC = AOAC International, ASAE = American Society of Agricultural Engineers, BSI = British Standard Institution, and AACC = American Association of Cereal Chemists.

Table 3. Summary of equilibrium moisture content (EMC)/equilibrium relative humidity (ERH) research for rice and rice components.

Citation	Country	Form or Product	Cultivar (type)[a]	Temp. (°C)	RH (%)	Path[b]	Tested or Developed Equations	Remark
Agrawal and Clary (1971)	USA	Rough	--	--	--	des	Langmuir, Brunauer, Herkins-Jura, Henderson, Day-Nelson, Chung-Pfost, Smith, Becker-Sallans, Haynes, polynomials, Strohman	Used published data
Aguerre et al (1983)	Argentina	Rough	Itape (medium-grain)	40, 50, 60, 70	3.6-82.3	des	Oswin, Halsey, Henderson	
Banaszek and Siebenmorgen (1990)	USA	Rough	Newbonnet (long-grain)	12.5, 15, 20, 30	50-90	ads	Mod-Henderson, Mod-Chung-Pfost, empirically developed regression eq.	
Basunia and Abe (1999)	Japan	Rough	Japonica (medium-grain)	17.8-45	56-89.3	ads	Mod-Henderson, Mod-Chung-Pfost, Mod-Oswin, Mod-Halsey	
Basunia and Abe (2001)	Japan	Rough	Japonica (medium-grain)	11.8-51	37.1-89.7	des	Mod-Henderson, Mod-Chung-Pfost, Mod-Oswin, Mod-Halsey	
Benado and Rizvi (1985)	USA	Milled (ground)	--	10, 20, 30	--	ads des	--	
Breese (1955)	British West Indies	Rough	Joya (short-grain)	25	10-90	ads des	--	
Chang (1987)	Taiwan	Rough	Tainung No. 67	15, 25, 35	33-98	ads des	Empirically modified Henderson	
Chen (2000)	Taiwan	Rough, brown	--	5, 15, 25, 35, 50	--	ads des	Mod-Henderson, Chung-Pfost, Mod-Oswin, Mod-Halsey	
Chen and Clayton (1971)	USA	Rough, undermilled, polished	--	--	--	--	Henderson, Mod-Henderson, Chen, Mod-Chen, empirically developed eq.	Used published data
Chen and Jayas (1998)	Canada	Rough	--	--	--	--	GAB[c]	Used published data
Chen and Morey (1989a)	USA	Rough, brown	--	--	--	des	Mod-Henderson, Chung-Pfost, Mod-Halsey, Mod-Oswin	Used published data
Chen et al. (1984)	USA	Bran (flour)	--	23	11-98	sor	--	
Choi (2005)	Korea	Rough, brown	Nampyung	5-45	16-88.4	ads des	Mod-Henderson, Mod-Chung-Pfost, Mod-Oswin, Mod-Halsey	
Chung and Verma (1991)	USA	Rough	Tebonnet (long-grain)	15, 23	--	sor	Mod-Henderson, Chung-Pfost, Sabhah, empirically developed near quasi-static eq.	
Coleman and Fellows (1925)	USA	Rice	--	25	--	sor	--	
Fan et al. (2000)	USA	Rough, milled	Kaybonnet (long-grain), Cypress (long-grain), Bengal (medium-grain)	4, 21, 38	11-96	sor	Mod-Chung-Pfost, empirically developed eq.	
Gencturk et al. (1986)	USA	Wild rice	Zizania aquatica	--	--	sor des	GAB, Day-Nelson, Chen-Clayton, Mod-Halsey	
Goneli et al. (2007)	Brazil	Rough	Urucuia	10, 20, 30, 40, 50	11-84	ads des	Chung-Pfost, Copace, Mod-Halsey, Mod-Henderson, Mod-Oswin	
Henderson (1970)	USA	Rough	Colusa	22.2-25.6	--	--	--	
Hogan and Karon (1955)	USA	Rough	Zenith	26.7-43.9	--	des	Harkins-Jura, BET[d]	

of theoretically or empirically based equation. These equations are developed from equilibrium data collected through adsorption, desorption, or a combination of both (*ASABE Standards*, 2007; Sun, 1999; Sun and Byrne, 1998). Van den Berg and Bruin (1981) compiled 77 EMC/ERH equations. Several researchers produced equilibrium isotherms for

Table 3 (continued). Summary of equilibrium moisture content (EMC)/equilibrium relative humidity (ERH) research for rice and rice components.

Citation	Country	Form or Product	Cultivar (type)[a]	Temp. (°C)	RH (%)	Path[b]	Tested or Developed Equations	Remark
Houston (1952)	USA	Brown	Caloro	25	11-93	sor	--	
Houston and Kester (1954)	USA	Parboiled, quick-cooking	Long-grain	25, 37.8	11-93	sor	--	
Iguaz and Virseda (2007)	Spain	Rough	Lido (medium-grain)	40, 50, 60, 70, 80	14-90	des	Mod-Henderson, Mod-Chung-Pfost, Mod-Oswin, Mod-GAB, Mod-Halsey	
Jindal and Siebenmorgen (1994)	USA	Rough	Tebonnet (long-grain)	25	25-90	des	Mod-Chung-Pfost	
Juliano (1964)	Philippines	Rough	Peta, Taichung 65, 46, Malagkit -Sungsong	27.5, 32.5	44-96.5	ads des	--	
Kachru and Matthes (1976)	USA	Rough	Starbonnett	19.1-42.4	5-90	ads des	Empirically developed eq.	
Kameoka et al. (1986)	Japan	Rough, brown, hull	Nippon bare (short-grain)	20, 30, 40	11.2-85	des	Dubinin-Astakhov, empirically modified Dubinin-Astakhov eq.	
Karon and Adams (1949)	USA	Rough, head, polished, bran, hull	Rexora	25	11.1-92.5	sor	--	
Keum et al. (2000)	Korea	Rough, brown, white, hull	Odae	20, 30, 40	11.2-85.1	des	Mod-Henderson, Chung-Pfost, Mod-Oswin	
Lu and Siebenmorgen (1992)	USA	Rough, brown, white	Lemont (long-grain), Newbonnet (long-grain)	12- 50.2	84-90, 75	ads	--	‘
Pfost et al. (1976)	USA	Rough	--	--	--	--	Mod-Henderson, Chung-Pfost, Day-Nelson, Chen-Clayton, Strohman-Yoerger	Used published data
Pixton and Warburton (1975)	England	Bran, parboiled bran	Burma, Tanzania, S. Africa, India	15, 25, 35	--	ads des	--	
Putranon et al (1979)	Australia	Rough	Inga, Calrose	10, 20, 25, 30, 38	--	ads des	Empirically developed eq.	
Rangaswamy (1973)	India	Rice	--	27-28	30-100	ads des	--	
Rao (1939)	India	Polished	Nagapur Sanna	30	--	ads des	--	
Reddy and Chakraverty (2004)	India	Paddy (raw and parboiled), brown, bran	IR-36 (long-grain)	13, 30, 40	20-80	ads	Mod-Henderson, Mod-Chung-Pfost, Mod-Halsey, GAB	
San Martin (2001)	Spain	Rough	Lido (medium-grain)	0-35	24-95	ads	Mod-Henderson, Mod-Chung-Pfost, Mod-Halsey, Mod-Oswin, GAB	
Sun (1999)	Ireland	--	--	--	--	--	Mod-Henderson, Mod-Chung-Pfost, Mod-Oswin, Strohman-Yoerger	Used published data
Yu and Wang (2006)	China	Rough	--	30, 40, 50	5-85	ads des	Mod-Henderson, Mod-Chung-Pfost, Mod-BET	
Zuritz et al. (1979)	USA	Rough	CSM5 (medium-grain)	10, 20, 25, 30, 40	11-97	des	Chung-Pfost, Day-Nelson, empirically modified Henderson eq.	

[a] Type refers to the dimensional classifications of short-, medium-, or long-grain.
[b] Refers to whether the samples reached equilibrium through desorption (des), adsorption (ads), or a combination of adsorption and desorption (sor).
[c] GAB = Guggenheim-Anderson-de Boer.
[d] BET = Brunauer-Emmett-Teller.

rough rice, while others did so for brown rice, polished rice, parboiled rice, rice bran, rice hull, ground rice, and quick-cooking rice, as well as other grains and agricultural products. Table 3 summarizes EMC/ERH research related to rice and rice components and lists the models tested to describe this data.

Rice Isotherm Equations

As seen in table 3, several equations have been developed to describe quantitatively the EMC of rice and rice components. Agrawal and Clary (1971) evaluated eleven sorption equations using published data for rough rice desorption isotherms from four sources and found that the Strohman and Yoerger (1967) empirical equation for predicting sorption phenomenon was most accurate. Several studies have further evaluated the Strohman-Yoerger equation. Pfost et al. (1976) compared five equations (Modified Henderson, Chung-Pfost, Day-Nelson, Chen-Clayton, and Strohman-Yoerger) using published desorption isotherms for yellow dent corn and showed that the Strohman-Yoerger equation produced the least standard error of estimate. However, due to its complexity and difficulty of use, the researchers opted to use the Modified Henderson and Modified Chung-Pfost equations for subsequent analysis of sorption behavior of grain, including rough rice.

Sun (1999) compared the Modified Chung-Pfost, Modified Henderson, Modified Oswin, and Strohman-Yoerger equations for describing 763 published EMC data points for rice from different authors. Results showed that all four equations produced similar errors, but the Strohman-Yoerger equation, which has an extra coefficient, was best for describing rice EMC/ERH isotherms.

Numerous other models have been considered as a means of predicting EMC/ERH relationships, most notably the Henderson, Chung-Pfost, Oswin, and Halsey equations. Zuritz et al. (1979) compared the Day-Nelson, Chung-Pfost, and empirically modified Henderson equations for describing EMC/ERH rough rice data. They found no difference among the three and stated that each could be used to predict EMC data. Aguerre et al. (1983) compared the Henderson equation to the Oswin and Halsey equations in modeling rough rice EMC data over a temperature range of 40°C to 70°C. Their findings showed the Henderson equation as the best equation for predicting experimental data.

Chen and Morey (1989a) used rough and brown rice data to compare the Modified Henderson, Modified Chung-Pfost, Modified Halsey, and Modified Oswin equations, concluding that, with the exception of the Modified Halsey equation, which is normally recommended for high-protein products, the other three equations could adequately describe some or all of the rice data. This assessment of the four equations was supported by Chen (2000), who suggested that the Modified Henderson and Chung-Pfost equations were good predictors of sorption parameters for both rough and brown rice, while the Modified Oswin was adequate for brown rice only. Choi (2005) further supported these results, using the same four equations to predict measured adsorption and desorption EMC/ERH values for rough and brown rice between 5°C and 45°C for MCs between 8.7% and 25% (d.b.). Results showed that the Modified Oswin equation was best in describing the adsorption EMC and adsorption EMC/ERH of brown rice, while the Modified Chung-Pfost equation best described rough rice ERH data and desorption EMC/ERH data of both rough and brown rice.

In an evaluation of the Modified Henderson, Chung-Pfost, and Modified Oswin equations, Keum et al. (2000) used EMC values determined at three temperatures (20°C, 30°C, and 40°C) and eight RHs (11.2% to 85%) for rice and rice components. Results indicated that the Modified Henderson and Chung-Pfost equations could serve as good predictors, but the Modified Oswin equation was not acceptable for rough rice, white rice, and rice hull.

Basunia and Abe (1999, 2001) analyzed data to compare these same equations for prediction of adsorption and desorption EMC data of medium-grain rough rice. Under a wide range of rewetting conditions (17.8°C to 45.0°C and 56.0% to 89.3% RH), the Modified Chung-Pfost equation best described EMC/ERH adsorption isotherms of rough rice; however, the authors indicated that the error parameters obtained with the four equations were similar, suggesting that any of the four could be used to predict medium-grain rough rice EMC/ERH data. In predicting desorption isotherms for the range of air temperatures and RHs studied (11.8°C to 51°C and 37.1% to 89.7% RH), the Modified Chung-Pfost equation produced the least error parameter values, followed by the Modified Henderson equation.

Gencturk et al. (1986) modeled the EMC/ERH data of processed wild rice and unprocessed wild rice to the Guggenheim-Anderson-deBoer (GAB), Day-Nelson, Chen-Clayton, and Modified Halsey equations. They reported that the GAB equation described the data very well, and that two other equations, the Day-Nelson and Modified Halsey, produced reasonably good results. However, Chen and Jayas (1998) evaluated the GAB equation for describing sorption data of several food materials, including rice, beans, corn, sorghum, soybeans, and potatoes, and reported reduced ability to describe data with changes in temperature. The authors also noted that the ERH vs. EMC mathematical relationship was very complex, and the residual plots revealed that two regions of deviation existed for most starchy grains when this equation was applied.

Four EMC/ERH equations (Modified Henderson, Modified Chung-Pfost, Modified Halsey, and GAB) were used to model data from various rice forms (raw and parboiled paddy, brown rice, and bran) by Reddy and Chakraverty (2004). The study reported that the standard error of estimates and the mean relative percent error for all rice forms were lowest with the GAB equation, followed by the Modified Chung-Pfost and Modified Henderson equations, and that error parameters for the Modified Halsey equation were relatively high.

San Martin et al. (2001) further compared the GAB equation's ability to describe adsorption EMC data for medium-grain rough rice to that of the Modified Chung-Pfost, Modified Halsey, Modified Henderson, and Modified Oswin equations. The authors concluded that the Modified Chung-Pfost equation yielded the lowest residual values and was considered the best model for EMC/ERH relationships.

Most recently, Iguaz and Virseda (2007) compared five equations (Modified Henderson, Modified Chung-Pfost, Modified Halsey, Modified Oswin, and Modified GAB) for predicting equilibrium data of rough rice between 40°C and 80°C. The GAB equation proved best for predicting rough rice EMC and its temperature dependence. The Modified Chung-Pfost and Henderson equations were found to be acceptable, while the Modified Halsey and Modified Oswin equations did not conform well to the experimental data.

Some less frequently cited models may also be appropriate for predicting sorption isotherms of rice and rice components. Kachru and Matthes (1976) developed an empirical sorption model that described EMC as a polynomial function of RH and a linear function of temperature for rough rice. Putranon et al. (1979) showed that the ERH of rough rice is a polynomial function of MC and a linear function of temperature. Banaszek and Siebenmorgen (1990) developed a regression equation and modified two existing EMC equations, the Modified Henderson and Modified Chung-Pfost, to predict adsorption EMCs for various air conditions and initial MCs of rough rice. A Re-modified Henderson equation appeared to be the best overall predictor of EMC in the range of 70% to 90% RH and 12.5°C to 30°C. Fan et al. (2000) developed an EMC equation that included variables of temperature, RH, and cultivar, using two long-grain and one medium-grain cultivars.

Quantitative Standards

ASABE Standard D245.6 (*ASABE Standards*, 2007) lists the Modified Henderson, Modified Chung-Pfost, Modified Halsey, Modified Oswin, and GAB equations for predicting EMC/ERH values of plant-based agricultural materials and their products. However, the Modified Henderson and Modified Chung-Pfost equations are most frequently cited and recommended for describing sorption behavior of rice. With the exception of the GAB equation, which does not include the effect of sorption temperature, these equations each have three empirically determined parameters that can be solved explicitly for ERH as a function of temperature and EMC, or for EMC as a function of temperature and ERH. The equations are as follows, and the symbols are defined as: M = EMC (% d.b.), RH = ERH (decimal), T = temperature (°C), and A, B, and C are equation coefficients (empirical constants).

(1) Modified Henderson equation (Thompson et al., 1968; *ASABE Standards*, 2007):

$$RH = 1 - \exp\left[-A(T + C)M^{B}\right]$$

$$M = \left[\frac{\ln(1 - RH)}{-A(T + C)}\right]^{1/B}$$

(2) Modified Chung-Pfost equation (Pfost et al., 1976; *ASABE Standards*, 2007):

$$RH = \exp\left[-\frac{A}{T + C}\exp(-B \cdot M)\right]$$

$$M = \frac{\ln A}{B} - \frac{1}{B} \cdot \ln\left[-(T + C) \cdot \ln RH\right]$$

(3) Modified Halsey equation (Iglesias and Chirife, 1976; *ASABE Standards*, 2007):

$$RH = \exp\left[-\frac{\exp(A + B \cdot T)}{M^{C}}\right]$$

$$M = \left[\exp(A + B \cdot T)\right]^{1/C} \cdot \left[-\ln RH\right]^{-1/C}$$

(4) Modified Oswin equation (Oswin, 1946; *ASABE Standards*, 2007):

$$RH = \left[\left(\frac{A + B \cdot T}{M}\right)^{C} + 1\right]^{-1}$$

$$M = (A + B \cdot T)\left[\frac{1 - RH}{RH}\right]^{-1/C}$$

To determine the coefficients A, B, and C for a set of EMC/ERH data in equations 1 through 4, and to select the most appropriate equation for describing experimental data, many researchers have utilized statistical packages, such as the Statistical Analysis System (Banaszek and Siebenmorgen, 1990; Choi, 2005; Fan et al., 2000; Keum et al., 2000; Yu and Wang, 2006; Chung and Verma, 1991) and SPSS (Basunia and Abe, 1999, 2001; Sun, 1999; Yu and Wang, 2006). However, some researchers used self-designed nonlinear least squares regression programs (Chen, 2000; Chen and Morey, 1989a; Reddy and Chakraverty, 2004; Kameoka et al, 1986; Putranon et al., 1979). The predictive ability of the equations was compared using quantitative standards like the standard error of estimate (SEE), mean relative deviation (MRD), coefficient of determination (R^2), and root mean square error (RMSE).

Factors Affecting Rice Hygroscopic Equilibria Data

Despite the availability of many EMC/ERH equations, there is not an apparent superior equation that accurately describes the EMC/ERH relations for all rice cultivars, components, and products over a broad range of environmental conditions. Therefore, there is a need to develop appropriate EMC/ERH equation constants for a specific product (Basunia and Abe. 2001; Sun, 1999). It is also important to understand the effects imparted on EMC/ERH relationships by intrinsic characteristics of the product, as well as extrinsic factors such as temperature, RH, and other processing conditions.

Air Temperature and Relative Humidity Effects

Environmental conditions, specifically temperature and RH of the surrounding air, primarily determine EMC/ERH relationships. The sorption behavior of all rough rice components is temperature-dependent at any given RH. However, the effect of temperature diminishes as RH increases (Hogan and Karon, 1955; Putranon et al., 1979; San Martin et al., 2001). Kameoka et al. (1986) explained that the reason for this discrepancy in temperature dependence is that the binding energy for water inside the kernel decreases with increasing temperature. The increase in MC with increasing RH at a given temperature is not linear, increasing at faster rates at the greatest RHs (Coleman and Fellows, 1925). This concept is graphically illustrated by the typical sigmoid shape of isotherm curves, depicting an inflection point, a linear region, and a reflection point (Agrawal and Clary, 1971). To fundamentally explain sorption behavior, Hogan and Karon (1955) stated that adsorption of water by rough rice occurs in three stages. The first stage, 0% to 7% MC (d.b.), represents the adsorption of a monolayer of water molecules. The second stage extends from approximately 7% to 14% MC (30% to 65% RH), and represents the formation of a second molecular layer of water. This intermediate stage is characterized by a linear increase in MC with increasing RH. The third stage may be considered a multilayer addition of water from approximately 14% MC (d.b.) to saturation.

Hysteresis

Desorption isotherms are reflective of the drying process, while adsorption isotherms represent rewetting conditions, such as those that may occur during long-term storage (Chen, 2000; Sun and Byrne, 1998; Sun, 1999). Equilibrium MCs attained through desorption at a given temperature and RH will not equal those attained through adsorption under the same temperature/RH conditions. The EMC attained by drying a product under a certain temperature and RH will be greater than when the product is wetted under those conditions. The difference between the two MCs is defined as hysteresis (Chen, 2000; Hulasare et al., 2001). Kachru and Matthes (1976) stated that at a constant temperature, the hysteresis differential is at its maximum in the middle portion of the RH range and converges to zero at the least and greatest RHs. This work showed a maximum hysteresis value of 1.25 percentage points (d.b.) at 526°R (approx. 19°C) and 60% RH.

The hysteresis phenomenon has been observed by various researchers studying rice (Breese, 1955; Benado and Rizvi, 1985; Chen, 2000; Choi, 2005; Henderson, 1952, 1970; Houston, 1952; Houston and Kester, 1954; Juliano, 1964; Kachru and Matthes, 1976; Pixton and Warburton, 1975; Putranon et al, 1979). Houston (1952) showed that when Caloro brown rice attained equilibrium between 40% and 65% RH by desorption at 25°C, the MC was nearly one percentage point greater than that attained by adsorption at the same RHs and temperature. Breese (1955) found a maximum MC difference of 1.8 percentage points between desorption and adsorption EMCs at 25°C for short-grain rough rice of the Joya cultivar. Putranon et al. (1979) found a maximum hysteresis value of about one percentage point EMC in paddy of the Inga and Calrose cultivars.

Researchers have demonstrated that temperature also influences the magnitude of hysteresis, although observations have been somewhat conflicting. Kachru and Matthes (1976), Benado and Rizvi (1985), and Goneli et al. (2007) reported that the effect of hysteresis declined markedly with increased drying temperatures. Chen (2000), however, reported that the hysteresis effect was similar at drying temperatures of 25°C and 50°C, even though the EMC isotherm curve tended to be lower for samples dried at the greater temperature.

The literature also suggests that rice form and/or product influences the extent of hysteresis. Houston and Kester (1954) showed that the hysteresis effect in parboiled and quick-cooking rice was greater than in raw white and brown rice. Conversely, Pixton and Warburton (1975) reported that parboiled rice bran exhibited lesser hysteresis effect than non-parboiled rice bran.

Henderson (1970) and Kachru and Matthes (1976) investigated hysteresis in rough rice and found that although hysteresis occurred, its magnitude decreased with repeated cycles of drying and rewetting. Benado and Rizvi (1985) reported that at 10°C, where the amount of hysteresis was greatest during the first cycle of experiments, the second-cycle isotherms of ground milled rice showed no hysteresis. The same phenomenon was observed at 20°C and 30°C. Regarding the disappearance of the hysteresis effect, Rao (1945) explained that kernels are essentially organogels, which can hold water within the cavities of their rigid structures. The walls of the cavities become elastic by virtue of their swelling properties during water uptake. However, repeated drying/wetting cycles cause the cavities to lose elasticity, and thus the ability to entrap water, resulting in a diminished hysteresis effect. Table 4 lists published hysteresis data for rice.

Rice Component and Processing Effects

In considering the equilibrium data for the components of a rough rice kernel, the literature is consistent in that for any given temperature and RH, milled and brown rice demonstrated the greatest EMCs, generally followed by that of rough rice (all components intact), bran, and hull (Karon and Adams, 1949; Houston, 1952; Reddy and Chakraverty, 2004; Choi, 2005; Fan et al., 2000; Keum et al., 2000; Lu and Siebenmorgen, 1992; Kameoka et al., 1986). Keum et al. (2000) reported that EMC values of white rice were greater than brown rice. Fan et al. (2000) reported that the average increase in EMC of milled rice over that of rough rice at 4°C, 21°C, and 38°C across three cultivars (long-grains Kaybonnet and Cypress and medium-grain Bengal) was 0.7 to 1.1 percentage points. The difference in EMC between rough and milled rice is primarily due to the hull, which has a lower EMC than the endosperm, and which comprises approximately 20% of the rough rice mass (Fan et al., 2000). Karon and Adams (1949), Kameoka et al. (1986), and Keum et al. (2000) showed that under equilibrium conditions, hulls contained less moisture than did other rice fractions. Since rough rice comprises brown rice and hull, the weighted average rough rice EMC, based on brown rice and hull EMCs, was in close agreement with the actual rough rice EMC values (Kameoka et al., 1986).

Reddy and Chakraverty (2004) reported that parboiled paddy and brown rice showed lesser EMC values than those of raw paddy and brown rice, but raw bran showed lesser EMC values than those of bran from parboiled rice. Houston and Kester (1954) reported that at 25°C, parboiled milled rice EMCs were slightly greater than those of non-parboiled milled rice and almost identical to those of non-parboiled brown rice in the RH range of 10% to 60%. Quick-cooking rice (subjected to partial cooking, washing, and drying) had lesser moisture content at 25°C than parboiled milled, non–parboiled brown, and non-parboiled milled rice. Houston and Kester explained that since parboiled and quick-cooking rice had been subjected to moist heat, the starch had been partially gelatinized, which would be expected to cause a different moisture-humidity relationship than that of non-parboiled products. The removal of soluble matter in the washing and drying process of quick-cooking rice may also result in further differences.

Cultivar Effects

Rice cultivars have different EMC/ERH relationships. Lu and Siebenmorgen (1992) reported that the EMCs of long-grain Lemont cultivar rough, brown, and white rice were generally greater than those of long-grain Newbonnet cultivar when air temperatures were below 35°C. At temperatures of 40°C and 50°C, the trend reversed, with Newbonnet cultivar

Table 4. Summary of hysteresis data for rice and rice products, expressed as the difference in equilibrium moisture content (*italicized numbers*) at given equilibrium relative humidity values (non-italicized numbers).

Reference	Form or Product	Description	Temp. (°C)	ERH (%) *EMC Difference between Desorption and Adsorption*[a]									
Breese (1955)	Rough rice	Joya (short grain)	25	10	20	30	40	50	60	70	80	90	
				0.7	*1.2*	*1.1*	*1.5*	*1.6*	*1.8*	*1.6*	*1.2*	*0.1*	
Juliano (1964)	Rough rice	Peta (Indica, non-waxy)	27.5				44.5		64	75	84		
							1.5		*1.1*	*1.2*	*1.0*		
			32.5				43.5		63	75	84		
							1.4		*1.4*	*1.3*	*0.8*		
		Taichung 65 (Japonica, non-waxy)	27.5				44.5		64	75	84		
							1.4		*0.9*	*1.1*	*1.8*		
			32.5				43.5		63	75	84		
							1.4		*1.0*	*0.9*	*0.5*		
		Malagkit Sungsong (Indica, waxy)	27.5				44.5		64	75	84		
							1.4		*1.1*	*0*	*0.9*		
			32.5				43.5		63	75	84		
							1.2		*1.1*	*1.1*	*0.9*		
		Taichung glu 46 (Japonica, waxy)	27.5				44.5		64	75	84		
							1.4		*1.1*	*0.9*	*0.8*		
			32.5				43.5		63	75	84		
							1.4		*1.0*	*0.9*	*1.1*		
Haque et al. (2007)	Rough, brown, milled rice	Hybrid (CNSGC-6)	30.0			36.15		51.4		73.14	80.27	97.00	
						0.7[b]		*1.2*		*1.0*	*0.6*	*0.3*	
						1.1		*1.3*		*1.0*	*0.5*	*0.3*	
						0.6		*1.1*		*1.0*	*0.8*	*0.4*	
			40.0			32.88	48.42			71.00	79.43	96.41	
						0.8	*0.7*			*0.9*	*0.3*	*0.3*	
						0.7	*0.9*			*0.9*	*0.5*	*0.2*	
						0.6	*0.8*			*0.9*	*0.5*	*0.4*	
			50.0		29.21		45.44		69.04	79.02		95.82	
					0.6		*0.8*		*0.8*	*0.5*		*0.2*	
					0.4		*0.9*		*1.2*	*0.4*		*0.1*	
					0.7		*0.6*		*1.0*	*0.4*		*0.4*	
Houston (1952)	Brown Rice	Caloro	25				43.7	53.3	64.4				
							0.9	*0.9-1*	*0.8-1*				
Houston and Kester (1954)	Quick-cooking rice	(long grain)	25				43.7	53.3	64.4				
							0.4	*1.5*	*2.2*				
Rangaswamy (1973)	Rice (form not specified)	*Oryza sativa*	27-28			30		50	60	70	80	90	100
						0.9		*1.1*	*1.8*	*1.8*	*1.5*	*0.3*	*0.4*

[a] Difference in EMC between desorption and adsorption treatment is expressed in percentage points (w.b.).
[b] The EMC differences for each temperature/ERH combination, listed from top to bottom, represent rough rice, brown rice, and milled rice, respectively.

showing greater EMCs than Lemont. Putranon et al. (1979) showed that the effect of cultivar (Inga and Calrose) on isotherms was small, with a maximum MC difference of about 0.5 percentage points. Pixton and Warburton (1975) observed that desorption and adsorption EMCs for Burma rice bran were greater than South African, Indian, and Tanzanian rice brans at 65% RH.

Composition of rice may play a role in explaining cultivar differences (Juliano, 1990). Juliano (1964) stated that waxy rice, in which the starch is essentially amylopectin, had significantly greater MCs than non-waxy cultivars at RHs above 75%. Fan et al. (2000) suggested that the difference in EMC observed among cultivars could be attributed in part to grain type. Bengal rough rice, a medium-grain type, produced greater EMC values than long-grain cultivars Kaybonnet and Cypress at RHs greater than 40%. This latter observation by Fan et al. (2000) could partially corroborate the explanation by Juliano (1964), in that medium-grain cultivars generally have greater amylopectin contents than long-grain cultivars.

Growing Location and Harvest MC Effects

To determine the influence of growing location on sorption isotherms, Putranon et al. (1979) collected Inga rough rice samples from three sites in Australia and determined isotherms for each at temperatures of 15°C and 25°C. Results showed that growing location had no significant effect on the isotherms. Fan et al. (2000) reported that neither harvest location nor harvest MC had a significant effect on the EMCs of rough rice.

Conclusions

- Equilibrium MC/ERH properties have been determined primarily using static and dynamic methods to attain hygroscopic equilibrium, as well as direct gravimetric methods and indirect, ERH-measurement methods for collecting EMC/ERH data. The static approach generally requires longer durations and reflects conditions that occur during storage, while a dynamic approach may expedite equilibrium and provide insight into drying processes.
- Methods to determine MC of rice in EMC/ERH studies were not uniform. Different MC-determination methods may yield different water contents and resultant EMC/ERH data.
- Many sorption isotherm equations have been used to describe sorption behavior of grains, but only some are regularly cited to describe experimental data for rice and rice products. The most commonly investigated include the Modified Henderson, Modified Chung-Pfost, Modified Oswin, and Modified Halsey models. The Modified Henderson and Modified Chung-Pfost are most frequently recommended for describing the sorption behavior of rice.
- When comparing EMCs of rice kernel components at given temperatures and RHs, the EMC of milled and brown rice are greatest, generally followed by rough rice, bran, and hull.
- The hysteresis effect has been documented in rice and rice products. Research suggests that the magnitude of hysteresis is greater in the mid-RH range and declines with increasing temperature. Hysteresis also decreases with repeated cycles of drying and rewetting.
- Rice cultivars affect EMC/ERH relationships, but harvest location does not seem to have a significant effect.
- For each cultivar, there is an apparent need to generate EMC/ERH equation constants to optimize the description of equilibria data.

Future Work

This research summary indicates that rice type and variety have a significant effect on EMC/ERH relationships, as does the wide range of processing conditions to which products may be exposed. The hysteresis phenomenon plays an important role in understanding EMC/ERH theory and its practical application to modern grain processing. However, many questions remain with regard to the effects of storage, environmental control, and cultivar on its impact. Additionally, limited work has been done to evaluate the effect of adsorption/desorption processes on head rice yield (Siebenmorgen and Jindal, 1986; Jindal and Siebenmorgen, 1994; Shimizu et al., 2007) and head rice functional properties.

Today's rice industry is continually exploring new cultivars and growing practices that promote improved sustainability and yields in order to feed an increasing world population, projected to reach nine billion by 2050 (United Nations, 2008). As new cultivars are developed and produced, it will be necessary to determine EMC/ERH equation constants for each in order to optimize storage and processing parameters. Of particular significance are hybrid cultivars, currently estimated to account for 35% to 40% of U.S. long-grain acreage (B. Ottis, personal communication, 22 March 2010) and over 50% of production in China, the world's leading rice-producing nation (Peng, 2007). Hybrid cultivars, which offer significant yield advantages, are likely to increase in both number and production in coming years, providing opportunity for further EMC research. Another potential long-term approach to increased rice production is genetically modified (GM) varieties. In 2009, China's Ministry of Agriculture became the first to approve commercial production of GM rice, which may lead to further research and production trials by other countries and agencies. Should this technology become widely accepted in the next decade, EMC research will be warranted.

Additionally, specialty varieties, such as jasmine, basmati, wild, and organic rice, may serve as important EMC research topics. These varieties, which have traditionally been grown in specific geographic regions, are gaining popularity in many food sectors and are expanding into other growing regions. For example, the majority of current U.S. imported rice consists of specialty aromatic varieties (USDA, 2008). EMC research is necessary to maintain optimum quality of these products throughout the import and processing chain, and will also be important as domestic breeds are developed to compete with these import varieties.

The documented cultivar effect, paired with increased usage of hybrid and specialty rices, suggest that the ultimate goal in hygroscopic equilibrium research may be the identification of those rice constituents that most significantly affect, or interact to affect EMC. The development of a model to show the integrated effect of physiological attributes such as starch components (amylose and amylopectin), protein, lipid, and ash, may minimize the need for cultivar-specific EMC/ERH data.

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