HENDERSON 平衡含水率模式之修正及本省主要水稻與玉米之平衡含水率曲線*

Modification of Henderson's EMC Model and EMC Isotherms of Local Paddy and Corn

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摘　　要

本研究探討多種平衡含水率模式。本文作者將 Henderson 平衡含水率模式之推導過程加以修正，使其具有數學及物理意義；然後利用其他研究人員所得之平衡含水率實驗資料驗證該模式之有效性並求出有關之常數。至少在相對溼度30%～90%範圍內，Henderson 平衡含水率修正模式是很好用的。

另外，本研究並利用實驗求得本省主要水稻與玉米品種之平衡含水率數據，再導出在不同狀況下之平衡含水率模式。這些資料對於未來模擬作物乾燥與儲藏都很有用處。

主鍵語：含水率，模式。

Abstract

Several equilibrium moisture content (EMC) equations were reviewed. The derivation of Henderson's EMC equation was modified and corrected by the author to show its mathematical and physical meanings. Then, other researchers' EMC data was used to get related coefficients and test the equation's effectiveness. It is shown that the modified Henderson's EMC equation is very good at least in the 30% to 90% range of relative humidities.

Local varieties of rice and corn were also used to get EMC data, thus deriving respective EMC models for those rice and corn under different conditions. These models are very useful for future applications in the modeling of crop drying and storage.

Key words: moisture, models.

* 本文係根據作者於 1987 年 12 月 15—18 日在美國農業工程師學會冬季年會發表之論文 "Why Henderon's EMC equation works"(ASAE paper No. 87-6531) 補充含水率實驗資料及增加部分內容，擴編改寫而成。

INTRODUCTION

Equilibrium moisture contents of agricultural products can usually be obtained by conducting experiments at specified conditions. The specified conditions simply need to include three independent properties of the agricultural product and air system.

In the system, the dry matter of the product is of solid phase; water inside the product, normally of liquid phase; water vapor in the air, of gas phase; and dry air, definitely of gas phase. There are two susbstances of gas phase existed in the system, namely dry air and water vapor. The number of independent thermodynamic properties needed to specify the condition is three (2 + 1) because they are operated at a relatively low pressure thus can be treated as simple substances.

Generally, we may choose atmospheric pressure, temperature, and relative humidity as those three independent properties. The atmospheric pressure is or can be treated as constant in common cases. So, we fix the temperature and vary the relative humidities to get equilibrium moisture content curves for agricultural products. The EMC curves are then called EMC isotherms. It is necessary to analyze the thermodynamic states for deriving EMC models in order to better represent those EMC data.

The EMC models will be very useful for the study of grain drying and storage. However it must be kept in mind that those equilibrium moisture contents are still affected by the differing properties found among grain varieties as well as experimental procedures and methods.

The intended objectives of this study are:

1. Modify Henderson's EMC equation to show tis mathematical and physical meanings,
2. Conduct experiments for obtaining EMC data of Tainung No. 67 paddy and Tainan No. 5 corn, and
3. Derive modified Henderson's EMC equations for the above local varieties of rice and corn.

REVIEW OF EMC EQUATIONS

The most famous and probably first EMC equation in agricultural engineering was derived by Henderson (1952). The semi-empirical equation is as follows:

$$1 - (rh/100) = \exp(-k\,T\,M^n)$$

Where, rh: relative humidity, %,
M: moisture content, %,
T: absolute temperature, R, and
k, n: constants related to grains.

There was a minor mistake made by Henderson in his derivation of the equation. Also, Henderson's explanation of his derivation was not very clear. These will be discussed in the next section.

Day & Nelson (1965) proposed an EMC model similar to Henderson's as below:

$$1 - (rh/100) = \exp(-a\,M^b)$$

Chung & Pfost (1967) proposed the following EMC model:

$$\ln(rh/100) = (A/RT)\exp(-BM)$$

Young & Nelson (1967) described the adsorption and desorption EMC isotherms independently by using two EMC equations to handle hysteresis phenomenon. Actually, one EMC equation may be used-to get different sets of constant values for the desorption and adsorption processes spearately.

MODIFIED DERIVATION OF HENDERSON'S EQUATION

Based on the Gibb's adsorption equation, and combining it with other relationships and assumptions, Henderson got a partial differential equation form as below:

$$\partial \sigma = CRT \quad \partial \ln P \tag{1}$$

Where, σ: Surface tension of the adsorbed liquid, lb/ft
C: concentration of the adsorbed liquid, moles/square foot of wetted surface
R; Gas constant
T: Absolute Temperature, R
P: Vapor pressure of adsorbed liquid

A sketch of micro void space as shown in Fig. 1 proposed by Henderson is very useful for the following analysis. The sketch is based on the presumption of the quantity of water is a function of the surface S.

An indefinite integral of Formula (1) is

$$\sigma = CRT \ln P + C_1 \tag{2}$$

Formula (2) is shown in Fig. 2. From Fig. 2, it is very easy to see that the surface tension at vapor pressure = 0 is infinite. It is mathematically called an improper point or a point at infinity. Our interest in vapor pressure P is in the range of 0 through Ps, which is the saturated pressure of the liquid at T. It can also be shown that the integration of Formula (1) from 0 to P at any point less then Ps is improper.

Fortunately, there is a mathematical technique called mapping (Kreyszig, 1979) that can be applied here. In this special case, the mapping is called a linear

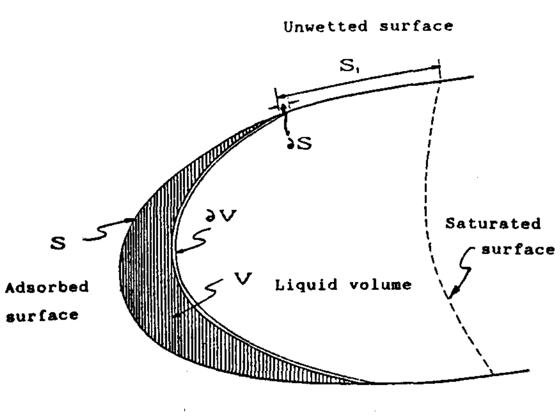


Fig. 1. Micro void space (Henderson, 1952)

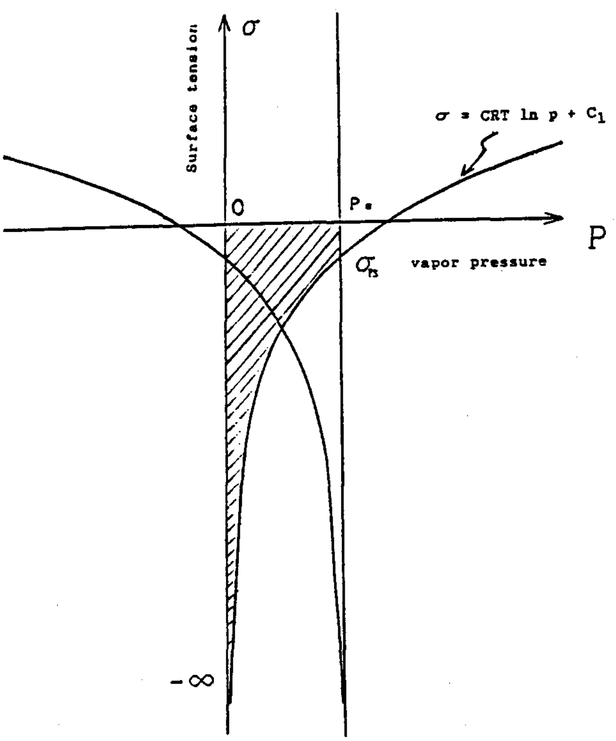


Fig. 2. Relationship between vapor pressure and surface tension

fractional transformation. The transformation is done by substituting (Ps-P) for P in Formula (1). Then we have:

$$\partial\sigma = \mathrm{CRT}\ \partial \ln (\mathrm{Ps} - \mathrm{P}) \qquad (3)$$

The indefinite integral form of Formula (3) is:

$$\sigma = \mathrm{CRT} \ln (\mathrm{Ps} - \mathrm{P}) + C_1 \qquad (4)$$

Formula (4) is also shown in Fig. 3.

The mapping we are concerned with is the shaded portion $-\infty$ 0 Ps σ_{Ps} in Fig. 2 on the shaded portion σ_{Ps} Ps O' $-\infty$ in Fig. 3. Now, the integration of Forrmula (1) at vapòr pressure from O to P is possible by using Formula (3) from Ps to (Ps–P). Does the transformation have a physical meaning other than the previously mentioned mathematical meaning? Yes, it does. Let's take a look at Fig. 1,

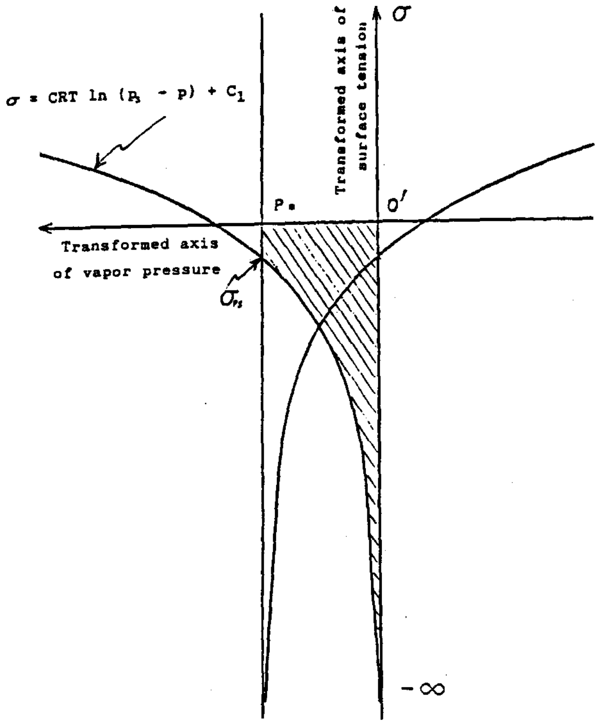


Fig. 3. Linear fractional transformation of Fig. 2.

where the shaded portion (the crescent moon shape on the left side) that is liquid before mapping becomes vapor after mapping. Actually, it will never happen in the real world. However, we may imagine it. This also shows that Formula (1)&(3) can be integrated only at vapor phase.

Now, the integration of Formula (3) Gives:

$$\sigma_{(Ps-P)} - \sigma_{Ps} = \mathrm{CRT} \ln [(\mathrm{Ps}-\mathrm{P})/\mathrm{Ps}] \qquad (5)$$

By the way, the minor mistake made by Henderson is that he took (P–Ps) instead of (Ps–P) for the substitution of P. (P–Ps) is a negative quantity which is not suitable for logarithm operations.

Rearrange Formula (5):

$$\ln [(\mathrm{Ps}-\mathrm{P})/\mathrm{Ps}] = (\sigma_{(Ps-P)} - \sigma_{Ps})/\mathrm{CRT} \qquad (6)$$

Combine Formula (6) with Henderson's original assumptions as follows:

$$C = k_1\ M^g \qquad (7)$$

$$1/(\sigma_{(Ps-P)} - \sigma_{Ps}) = k_2\ M^h \qquad (8)$$

we get,

$$\ln [(\mathrm{Ps}-\mathrm{P})/\mathrm{Ps}] = (k_1\, k_2\ R\, T\,)^{-1}\ M^{-(g+h)} \qquad (9)$$

Let $a = (k_1\, k_2\ RT)^{-1}$, $b = -(g + h)$

Then,

$$\ln [(\mathrm{Ps}-\mathrm{P})/\mathrm{Ps}] = a\, M^b \qquad (10)$$

Substitute rh/100 = P/Ps into Formula (10), we have:

$$1 - (rh/100) = \exp(a M^b) \qquad (11)$$

Henderson's EMC equation has the same form as Formula (11), only with minor differences in constants. This shows why Henderson's EMC equation works.

CHECK OF THE EQUATION USING SOME EXISTED EMC DATA

After doing two logarithm operations on Formula (11), we have:

$$\ln[-\ln(1 - (rh/100))] = \ln(-a) + b \ln M \qquad (12)$$

Formula (12) is a linear equation of the standard form of Y = A + BX. So, linear regression analysis can be applied for analyzing EMC data to get constants a & b and correlation coefficient R.

Juliano (1964) obtained several sets of EMC data of rough rice (Taichung No. 65) at 27.5 and 32.5 C. In this study, it is intended to relate relative humidities with moisture contents by using dry basis and wet basis for comparing their relationships. The linear regression analysis results are shown in Table 1. We can see that there are no differences in using dry or wet basis for expressing moisture contents. In both cases, we can be over 99% sure that ln [– ln (1–(rh/100))] and ln(M) are linearly related. However, the dry matter remains unchanged during drying or moistening, so, moisture content is expressed on a dry basis in this study for convenience.

Other EMC data (Breese, 1955; Karon & Adams, 1949; and Houston, 1953) of rough & brown rice are also used to get EMC model constants and their correlation coefficients as shown in Table 2. The reason for only choosing rice data for analysis is that rice is the main staple crop in Taiwan. From Table 2, we can still see those R squares are surprisingly high. This forces us to believe the Henderson EMC equation does in fact express the relationship between moisture content and relative humidity very well.

EMC'ISOTHERMS OF LOCAL PADDY AND CORN

Local varieties of Tainung No. 67 paddy (the most popular one in Taiwan)

Table 1. Basis comparisons of EMC model characteristics

Temp. C	Process	Moisture	a	b	R square
27.5	desorption	dry basis	–.0031385	2.1621	.9925
27.5	adsorption	dry basis	–.0095530	1.8239	.9965
32.5	desorption	dry basis	–.0046551	2.0414	.9943
32.5	adsorption	dry basis	–.013008	1.7239	.9977
27.5	desorption	wet basis	–.0017958	2.5002	.9945
27.5	adsorption	wet basis	–.0064479	2.0795	.9980
32.5	desorption	wet basis	–.0028237	2.3504	.9962
32.5	adsorption	wet basis	–.0091601	1.9574	.9989

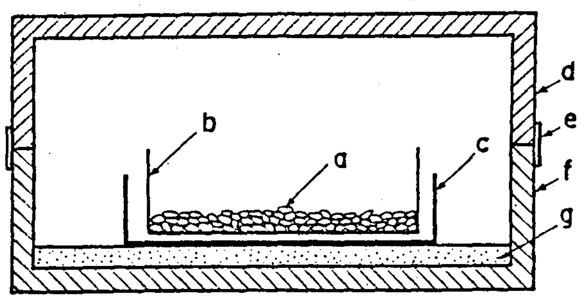
Note: 1. EMC data from Juliano, 1964.
2. a, b: EMC model constants.
3. R: correlation coefficient.

Table 2. Comparisons of using different EMC data

Material	Temp. C	Process	a	b	R square	Remarks
Rough rice	25	desorption	–.0038360	2.0942	.9988	1
Rough rice	25	adsorption	–.0074817	1.9464	.9972	1
Rough rice	25	desorption	–.0042446	2.0740	.9988	2
Rough rice	25	desorption	–.0027926	2.2585	.9954	3
Brown rice	25	desorption	–.0009970	2.4870	.9990	4

Note: 1. Breese, 1955.
2. Karon and Adams, 1949; naturally dried.
3. Karon and Adams, 1949; artificially dried.
4. Houston, 1952.
5. a, b, R: same as in Table 1.
6. MC used, dry basis.

and Tainan No. 5 corn were used to obtain EMC data for deriving respective models. The Conway diffusion units shown in Fig. 4 were used to maintain constant relative humidities as suggested by Wang *et. al.* (1980). Those relative humidities measured by Wang *et. al.* are shown in Table 3. Experimental temperatures were set at 15, 25, and 35 C for



a, sample; b, aluminum cap as the sample holder; c, inner dish; d, upper dish serving as the cover; e, contacting line sealed with elastic adhesive vinyl tape; f, lower dish serving as the main body; g, salt-saturated solution for maintaining constant humidity.

Fig. 4. Arrangements of the Conway diffusion unit (Wang *et. al.*, 1980)

Table 3. Salt-saturated solutions for maintaining constant relative humidities

Solid phase	Relative humidity, %
$K_2Cr_2O_7$	98.0
$BaCl_2$	90.1
KCl	84.2
$NaNO_3$	73.7
$Mg(NO_3)_2 \cdot 6H_2O$	52.8
$K_2CO_3 \cdot 2H_2O$	42.7
$MgCl_2 \cdot 6H_2O$	33.0
$KC_2H_3O_2 \cdot 2H_2O$	22.4

Note: All relative humidities measured at 25 C by Wang *et. al.*, 1980.

getting different EMC isotherms.

Moisture contents of all samples were determined by measuring the loss on heating 3 to 5 g samples (whole grain) in an air oven at 105 C for 24 h (paddy) and 72 h (corn).

At each condition, three samples were used to obtain the respective equilibrium moisture content. All moisture content data (wet basis) are shown in Table 4 (paddy) and Table 5 (corn). There are 6 sets of data for each product in all, that is, desorption and adsorption

Table 4. Moisture content data of Tainung No. 67 paddy

1. Desorption at 15°C			2. Adsorption at 15°C		
Relative humidity, %	Moisture content, % w.b. Exp. data	Average	Relative humidity, %	Moisture content, % w.b. Exp. data	Average
98.0	28.28 16.21* 26.75	27.51	98.0	19.98 11.59* 20.28	20.13
90.1	24.21 22.14 22.46	22.93	90.1	16.09 16.02 16.41	16.17
84.2	20.29 19.32 19.89	19.83	84.2	14.72 14.81 14.57	14.70
73.7	16.34 16.96 16.49	16.60	73.7	12.31 12.38 12.12	12.27
52.8	12.87 13.31 12.97	13.05	52.8	7.05 7.54 7.88	7.49
42.7	11.80 11.36 11.79	11.65	42.7	3.78 3.98 3.86	3.87
33.0	10.23 10.45 10.36	10.35	33.0	2.40 2.45 3.32	2.43
22.4	9.85 9.48 9.47	9.60	22.4	2.07 2.09 2.28	2.15

* Deleted because of error.

Table 4. Moisture content data of Tainung No. 67 paddy (cont.)

3. Desorption at 25 C			4. Adsorption at 25 C		
Relative humidity, %	Moisture content, % w.b. Exp. data	Average	Relative humidity, %	Moisture content, % w.b. Exp. data	Average
	26.78			17.50	
98.0	27.89	27.51	98.0	17.72	17.43
	27.86			17.07	
	19.78			16.79	
90.1	19.19	19.65	90.1	16.10	16.33
	19.97			16.09	
	17.06			14.53	
84.2	18.19	17.45	84.2	14.79	14.73
	17.09			14.87	
	14.40			12.27	
73.7	14.38	14.38	73.7	12.14	12.13
	14.35			11.97	
	11.43			8.54	
52.8	10.97	11.16	52.8	8.32	8.42
	11.09			8.40	
	10.54			6.26	
42.7	10.08	10.30	42.7	6.21	6.34
	10.30			6.57	
	9.57			4.15	
33.0	8.74	9.10	33.0	4.31	4.23
	8.97			45.57*	
	8.48			3.40	
22.4	8.91	9.01	22.4	3.29	3.26
	9.63			3.09	

* Deleted because of error.

Table 4. Moisture content data of Tainung No. 67 paddy (cont.)

5. Desorption at 35 C			6. Adsorption at 35 C		
Relative humidity, %	Moisture content, % w.b. Exp. data	Average	Relative humidity, %	Moisture content, % w.b. Exp. data	Average
	28.48*			21.46	
98.0	25.46	25.26	98.0	21.96	21.80
	25.05			21.99	
	18.85			16.20	
90.1	18.83	18.59	90.1	16.31	16.22
	18.08			16.14	
	15.77			13.63	
84.2	20.04*	15.93	84.2	13.68	13.69
	16.09			13.78	
	13.23			11.84	
73.7	13.16	13.17	73.7	12.09	11.91
	13.13			11.79	
	9.98			9.74	
52.8	10.37	10.58	52.8	8.50	8.97
	11.38			8.65	
	10.64*			7.59	
42.7	9.45	9.48	42.7	7.67	7.57
	9.51			7.44	
	7.74			6.93	
33.0	7.45	7.73	33.0	6.09	6.51
	8.01			1.67*	
	7.10			2.80	
22.4	6.34	6.65	22.4	2.88	2.70
	6.53			2.41	

* Deleted because of error.

Table 5. Moisture content data of Tainan No. 5 corn

1. Desorption at 15 C			2. Adsorption at 15 C		
Relative humidity, %	Moisture content, % w.b. Exp. data	Average	Relative humidity, %	Moisture content, % w.b. Exp. data	Average
	37.10			13.16*	
98.0	22.96*	36.84	98.0	20.68	19.97
	36.57			19.27	
	32.64			17.03	
90.1	31.91	32.41	90.1	17.58	17.22
	32.68			17.06	
	25.96			14.72	
84.2	25.81	25.89	84.2	14.40	14.59
	22.29*			14.64	
	20.43			11.88	
73.7	19.00	19.70	73.7	11.41	11.75
	19.66			11.96	
	13.91			6.52	
52.8	14.79	14.76	52.8	5.97*	6.49
	15.57			6.47	
	12.46			4.74	
42.7	14.68*	12.40	42.7	4.62	4.68
	12.33			4.00*	
	11.90			3.29	
33.0	11.46	11.68	33.0	3.27	3.27
	25.79*			3.26	
	11.09			2.90	
22.4	10.54	10.98	22.4	3.00	3.02
	11.32			3.16	

* Deleted because of error.

Table 5. Moisture content data of Tainan No. 5 corn (cont.)

3. Desorption at 25 C			4. Adsorption at 25 C		
Relative humidity, %	Moisture content, % w.b. Exp. data	Average	Relative humidity, %	Moisture content, % w.b. Exp. data	Average
	39.49			23.56	
98.0	40.24	39.87	98.0	13.75*	23.81
	17.80*			24.05	
	23.98			18.73	
90.1	23.38	23.68	90.1	18.10	18.35
	22.31*			18.22	
	18.37			16.14	
84.2	17.85*	18.41	84.2	15.86	15.93
	18.45			15.80	
	15.69			12.65	
73.7	15.38	15.38	73.7	12.61	12.65
	15.06			12.67	
	12.12			8.09	
52.8	11.97	12.01	52.8	7.76	8.01
	11.95			8.19	
	10.98			5.35	
42.7	11.19	11.04	42.7	5.61	5.48
	10.95			6.39*	
	9.86			4.50	
33.0	9.61	9.64	33.0	4.52	4.55
	9.44			4.63	
	8.88			3.85	
22.4	8.76	8.90	22.4	3.93	3.85
	9.05			3.77	

* Deleted because of error.

Table 5. Moisture content data of Tainan No. 5 corn (cont.)

5. Desorption at 35 C			6. Adsorption at 35 C		
Relative humidity, %	Moisture content, % w.b. Exp. data	Average	Relative humidity, %	Moisture content, % w.b. Exp. data	Average
	35.35			23.28	
98.0	34.88	35.25	98.0	23.43	23.36
	35.52			23.37	
	21.13			17.83	
90.1	21.17	21.14	90.1	17.94	17.83
	21.11			17.71	
	16.82			14.97	
84.2	16.94	16.87	84.2	15.03	15.00
	16.85			14.99	
	14.55			12.31	
73.7	15.90*	14.37	73.7	11.95	12.10
	14.18			12.03	
	10.99			7.83	
52.8	10.83	10.88	52.8	8.13	7.98
	10.83			7.97	
	10.33			6.56	
42.7	10.59	10.69	42.7	7.13	6.94
	11.14			7.14	
	9.47			4.94	
33.0	11.14*	9.17	33.0	7.85*	5.76
	8.86			4.47	
	7.64			3.41	
22.4	7.99	7.91	22.4	3.41	3.40
	8.08			3.39	

* Deleted because of error.

processes at three temperatures. In case of any error, then that experimental result was deleted and not used for calculation of the average of the moisture contents at that condition.

Those moisture content results are also shown in the second column (wet basis) and the third column (dry basis) in Tables 6 and 7.

Moisture contents (dry basis) are analyzed to get modified Henderson's EMC model's constants a, b and correlation coefficient R squares. They are shown in the fourth column in Tables 6 and 7.

With constants a and b available, we can get an EMC equation for each case. Moisture contents are calculated back by using these EMC equations at the experimental relative humidities. They are also shown in Tables 6 and 7 as well as the differences between calculated and experimental results.

Even though the values of R square for all cases are high, the moisture content differences between calculated and experimental results are not acceptable, especially at both end conditions, that is, relative humidities at 22.4% and 98.0%. Therefore, analyses are conducted by skipping experimental data at those conditions. Then, better results are obtained as shown in Table 8 and 9. They are constructed by the same procedures as Tables 6 and 7.

EMC curves in Fig. 5 and 6 are obtained by using respective constants a and b in Tables 8 and 9 (first, to get EMC equations; then, EMC curves.)

DISCUSSIONS

All R (correlation coefficient) squares for paddy in Table 8 are grater than 0.98 except the case of adsorption at 15 C. This means that we can be over 98% sure that the moisture contents of paddy and the relative humidities of the environment have the relationship depicted by Henderson's EMC equation.

The case of desorption at 15 C shows big differences such as 3.21%, 1.36%, 1.80% in the last column of Table 8. This is probably due to experimental or human error in determining moisture contents.

All R squares for corn in Table 9 are fairly good as are the differences between experimental and calculated M.C. data. Experimental M.C. data are also marked on Fig. 5.d and Fig. 6.d for quick comparisons. They are nicely fitted.

However, those adsorption isotherms are not consistent as shown in Fig. 5.d and Fig. 6.d. So, exercise caution when using those isotherms. It would be better to conduct more experiments to see what went wrong. Those desorption isotherms which can be well represented by the modified Henderson's EMC model

$$1 - (rh/100) = \exp(a\,M^b)$$

are summarized below with constants a's and b's values.

Product	Process	Temp., C	a	b
Paddy	Desorption	15	–.0045960	1.8613
Paddy	Desorption	25	–.0050229	1.9405
Paddy	Desorption	35	–.0089799	1.8344
Corn	Desorption	25	–.0031846	2.0614
Corn	Desorption	35	–.0027266	2.1816

CONCLUSIONS AND SUGGESTIONS

It is concluded that the Henderson's EMC equation is very good to describe the relationship between the moisture contents of agricultural products and the air relative humidities. However, it must be simplified to the following form:

Table 6. Comparisons of experimental and calculated moisture contents of Tainung No. 67 paddy (using whole original data)

a. Desorption at 15 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
98.0	27.51	37.95		36.74	26.87	–0.64
90.1	22.93	29.75	a = –0.0029845	28.22	22.01	–0.92
84.2	19.83	24.73		25.19	20.12	0.29
73.7	16.60	19.90	b = 1.9918	21.42	17.64	1.04
52.8	13.05	15.01		16.04	13.82	0.77
42.7	11.65	13.19		13.81	12.13	0.48
33.0	10.35	11.54	R^2 = 0.9782	11.70	10.48	0.13
22.4	9.60	10.62		9.30	8.51	–1.09

b. Adsorption at 15 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
98.0	20.13	25.20		34.73	25.78	5.65
90.1	16.17	19.29	a = –0.1337437	19.99	16.66	0.49
84.2	14.70	17.23		15.77	13.62	–1.08
73.7	12.27	13.99	b = 0.9516	11.23	10.09	–2.18
52.8	7.49	8.01		6.13	5.77	–1.72
42.7	3.87	4.03		4.48	4.28	0.42
33.0	2.43	2.49	R^2 = 0.9530	3.17	3.07	0.64
22.4	2.15	2.20		1.96	1.92	–0.23

c. Desorption at 25 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
98.0	27.51	37.95		33.42	25.05	–2.46
90.1	19.65	24.46	a = –0.0051346	25.31	20.20	0.55
84.2	17.45	21.14		22.46	18.34	0.89
73.7	14.38	16.80	b = 1.8910	18.93	15.92	1.54
52.8	11.16	12.56		13.96	12.25	1.09
42.7	10.30	11.48		11.92	10.65	0.35
33.0	9.10	10.01	R^2 = 0.9414	10.01	9.10	0.00
22.4	9.01	9.90		7.86	7.29	–1.72

Table 6. Comparisons of experimental and calculated moisture contents of Tainung No. 67 paddy (cont.)

d. Adsorption at 25 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
98.0	17.43	21.11		27.99	21.87	4.44
90.1	16.33	19.52	a = –0.0486336	18.78	15.81	–0.52
84.2	14.73	17.27		15.82	13.66	–1.07
73.7	12.13	13.80		12.37	11.01	–1.12
52.8	8.42	9.19	b = 1.3168	7.99	7.40	–1.02
42.7	6.34	6.77		6.37	5.99	–0.35
33.0	4.23	4.42	R^2 = 0.9609	4.95	4.72	0.49
22.4	3.26	3.37		3.51	3.39	0.13

e. Desorption at 35 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
98.0	25.26	33.80		30.82	23.56	–1.70
90.1	18.59	22.84	a = –0.0091670	22.89	18.63	0.04
84.2	15.93	18.95		20.14	16.77	0.84
73.7	13.17	15.17		16.78	14.37	1.20
52.8	10.58	11.83	b = 1.7665	12.11	10.80	0.22
42.7	9.48	10.47		10.22	9.28	–0.20
33.0	7.73	8.38	R^2 = 0.9845	8.48	7.82	0.09
22.4	6.65	7.12		6.55	6.15	–0.50

f. Adsorption at 35 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
98.0	21.80	27.88		31.54	23.98	2.18
90.1	16.22	19.36	a = –0.0556374	20.59	17.07	0.85
84.2	13.69	15.86		17.14	14.63	0.94
73.7	11.91	13.52		13.19	11.65	–0.26
52.8	8.97	9.85	b = 1.2323	8.26	7.63	–1.34
42.7	7.57	8.19		6.48	6.09	–1.48
33.0	6.51	6.96	R^2 = 0.9614	4.96	4.73	–0.17
22.4	2.70	2.77		3.42	3.31	0.61

Note: a, b, R, same as in Table 1.

Table 7. Comparisons of experimental and calculated moisture contents of Tainan No. 5 corn (using whole original data)

a. Desorption at 15 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
98.0	36.84	58.33		58.79	37.03	0.19
90.1	32.41	47.95	a = –0.0086387	41.42	29.29	–3.12
84.2	25.89	34.93		35.64	26.27	0.38
73.7	19.70	24.53	b = 1.5011	28.74	22.32	2.62
52.8	14.76	17.32		19.58	16.37	1.61
42.7	12.40	14.16		16.04	13.83	1.43
33.0	11.68	13.22	R^2 = 0.9465	12.88	11.41	–0.27
22.4	10.98	12.33		9.50	8.68	–2.30

b. Adsorption at 15 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
98.0	19.97	24.95		30.71	23.50	3.53
90.1	17.22	20.80	a = –0.0859147	19.17	16.08	–1.14
84.2	14.59	17.08		15.65	13.53	–1.06
73.7	11.75	13.31	b = 1.1150	11.71	10.49	–1.26
52.8	6.49	6.94		6.99	6.53	0.04
42.7	4.68	4.91		5.35	5.07	0.39
33.0	3.27	3.38	R^2 = 0.9728	3.98	3.82	0.55
22.4	3.02	3.11		2.64	2.57	–0.45

c. Desorption at 25 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
98.0	39.87	66.31		50.56	33.58	–6.29
90.1	23.68	31.03	a = –0.0175938	34.52	25.66	1.98
84.2	18.41	22.56		29.30	22.66	4.25
73.7	15.38	18.18	b = 1.3775	23.17	18.81	3.43
52.8	12.01	13.65		15.26	13.24	1.23
42.7	11.04	12.41		12.28	10.94	–0.10
33.0	9.64	10.67	R^2 = 0.8918	9.66	8.81	–0.83
22.4	8.90	9.77		6.94	6.49	–2.41

Table 7. Comparisons of experimental and calculated moisture contents of Tainan No. 5 corn (cont.)

d. Adsorption at 25 C

rh, %	Experimental MC, % wet basis	dry basis	EMC constants	Calculated MC, % dry basis	wet basis	Difference
98.0	23.81	31.25		33.54	25.12	1.31
90.1	18.35	22.47	a = –0.0557209	21.72	17.85	–0.50
84.2	15.93	18.95		18.03	15.27	–0.66
73.7	12.65	14.48	b = 1.2103	13.80	12.13	–0.52
52.8	8.01	8.71		8.57	7.90	–0.11
42.7	5.48	5.80		6.70	6.28	0.80
33.0	4.55	4.77	R^2 = 0.9869	5.10	4.85	0.30
22.4	3.85	4.00		3.50	3.38	–0.47

e. Desorption at 35 C

rh, %	Experimental MC, % wet basis	dry basis	EMC constants	Calculated MC, % dry basis	wet basis	Difference
98.0	35.25	54.44		42.44	29.79	–5.46
90.1	21.14	26.81	a = –0.0153729	29.74	22.92	1.78
84.2	16.87	20.29		25.52	20.33	3.46
73.7	14.37	16.78	b = 1.4779	20.51	17.02	2.65
52.8	10.88	12.21		13.89	12.20	1.32
42.7	10.69	11.97		11.35	10.19	–0.50
33.0	9.17	10.10	R^2 = 0.9076	9.08	8.32	–0.85
22.4	7.91	8.59		6.66	6.25	–1.66

f. Adsorption at 35 C

rh, %	Experimental MC, % wet basis	dry basis	EMC constants	Calculated MC, % dry basis	wet basis	Difference
98.0	23.36	30.48		31.75	24.10	0.74
90.1	17.83	21.70	a = –0.0437178	21.19	17.49	–0.34
84.2	15.00	17.65		17.81	15.12	0.12
73.7	12.10	13.77	b = 1.2996	13.89	12.20	0.10
52.8	7.98	8.67		8.92	8.19	0.21
42.7	6.94	7.46		7.08	6.62	–0.32
33.0	5.76	6.11	R^2 = 0.9929	5.50	5.21	0.55
22.4	3.40	3.52		3.87	3.72	0.32

Note: a, b, R, same as in Table 1.

Table 8. Comparisons of experimental and calculated moisture contents of Tainung No. 67 paddy (skipping some original data)

a. Desorption at 15 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
90.1	22.93	29.75		28.28	22.05	–0.88
84.2	19.83	24.73	a = –0.0045960	25.05	20.03	0.20
73.7	16.60	19.90		21.06	17.40	0.80
52.8	13.05	15.01	b = 1.8613	15.45	13.39	0.34
42.7	11.65	13.19		13.16	11.63	–0.02
33.0	10.35	11.54	R^2 = 0.9873	11.03	9.93	–0.42

b. Adsorption at 15 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
90.1	16.17	19.29	a = –0.1737281	24.04	19.38	3.21
84.2	14.70	17.23		18.21	15.41	0.71
73.7	12.27	13.99		12.25	10.91	–1.36
52.8	7.49	8.10	b = 0.8142	6.04	5.69	–1.80
42.7	3.87	4.03		4.18	4.01	0.14
33.0	2.43	2.49	R^2 = 0.9536	2.79	2.71	0.28

c. Desorption at 25 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
90.1	19.65	24.46	a = –0.0050229	23.57	19.08	–0.57
84.2	17.45	21.14		20.98	17.34	–0.11
73.7	14.38	16.80		17.76	15.08	0.70
52.8	11.16	12.56	b = 1.9405	13.20	11.66	0.50
42.7	10.30	11.48		11.32	10.17	–0.13
33.0	9.10	10.01	R^2 = 0.9853	9.55	8.72	–0.38

Table 8. Comparisons of experimental and calculated moisture contents of Tainung No. 67 paddy (cont.)

d. Adsorption at 25 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
84.2	14.73	17.27	a = –0.0677822	18.44	15.57	0.84
73.7	12.13	13.80		13.87	12.18	0.05
52.8	8.42	9.19	b = 1.1338	8.34	7.70	–0.72
42.7	6.34	6.77	R^2 = 0.9808	6.41	6.02	–0.32
33.0	4.23	4.42		4.79	4.57	0.34

e. Desorption at 35 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
90.1	18.59	22.84		21.84	17.92	–0.67
84.2	15.93	18.95	a = –0.0080799	19.13	16.18	0.25
73.7	13.17	15.17	b = 1.8344	16.19	13.93	0.76
52.8	10.58	11.83		11.83	10.58	–0.00
42.7	9.48	7.73	R^2 = 0.9885	10.05	9.13	–0.35
33.0	7.73	8.38		8.40	7.75	0.02

f. Adsorption at 35 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
90.1	16.22	19.36	a = –0.0138985	18.70	15.75	–0.47
84.2	13.69	15.86		16.43	14.11	0.42
73.7	11.91	13.52	b = 1.7465	13.65	12.01	0.10
52.8	8.97	9.85		9.82	8.94	–0.03
42.7	7.57	8.19	R^2 = 0.9963	8.27	7.64	0.07
33.0	6.51	6.96		6.85	6.41	–0.10

Note: a, b, R, same as in Table 1.

Table 9. Comparisons of experimental and calculated moisture contents of Tainan No. 5 corn (skipping some original data)

a. Desorption at 15 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
98.0	36.84	58.33	a = –0.0112461	58.03	36.72	–0.12
84.2	25.89	34.93		34.45	25.62	–0.27
52.8	14.76	17.32	b = 1.4410	18.46	15.58	0.82
42.7	12.40	14.16	R^2 = 0.9892	15.00	13.04	0.64
33.0	11.68	13.22		11.93	10.66	–1.02

b. Adsorption at 15 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
90.1	17.22	20.80	a = –0.1218171	21.97	18.01	0.79
84.2	14.59	17.08		17.33	14.77	0.18
73.7	11.75	13.31	b = 0.9528	12.35	10.99	–0.76
52.8	6.49	6.94		6.74	6.32	–0.17
42.7	4.68	4.91	R^2 = 0.9960	4.93	4.70	0.02
33.0	3.27	3.38		3.49	3.37	0.10

c. Desorption at 25 C

rh, %	Experimental MC, %		EMC constants	Calculated MC, %		Difference
	wet basis	dry basis		dry basis	wet basis	
84.2	18.41	22.56	a = –0.0031846	21.89	17.96	–0.45
73.7	15.38	18.18		18.72	15.77	0.39
52.8	12.01	13.65	b = 2.0614	14.15	12.40	0.39
42.7	11.04	12.41	R^2 = 0.9899	12.24	10.91	–0.13
33.0	9.64	10.67		10.43	9.45	–0.19

Table 9. Comparisons of experimental and calculated moisture contents of Tainan No. 5 corn (cont.)

d. Adsorption at 25 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
90.1	18.35	22.47	a = –0.0756658	23.27	18.88	0.53
84.2	15.93	18.95		18.90	15.90	–0.03
73.7	12.65	14.48	b = 1.0867	14.04	12.31	–0.34
52.8	8.01	8.71		8.26	7.63	–0.38
42.7	5.48	5.80	R^2 = 0.9941	6.28	5.91	0.43
33.0	4.55	4.77		4.63	4.43	–0.12

e. Desorption at 35 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
84.2	18.87	20.29	a = –0.0027266	19.83	16.55	–0.32
73.7	14.37	16.78		17.10	14.60	0.23
52.8	10.88	12.21	b = 2.1816	10.28	11.61	0.73
42.7	10.69	11.97	R^2 = 0.9732	11.45	10.28	–0.41
33.0	9.17	10.10		9.85	8.96	–0.21

f. Adsorption at 35 C

rh, %	Experimental MC, % wet basis	Experimental MC, % dry basis	EMC constants	Calculated MC, % dry basis	Calculated MC, % wet basis	Difference
90.1	17.83	21.70	a = –0.0357994	20.96	17.33	–0.50
84.2	15.00	17.65		17.77	15.09	0.09
73.7	12.10	13.77	b = 1.3699	14.04	12.31	0.21
52.8	7.98	8.67		9.22	8.44	0.46
42.7	6.94	7.46	R^2 = 0.9940	7.41	6.90	–0.04
33.0	5.76	6.11		5.83	5.51	–0.25

Note: a, b, R, same as in Table 1.

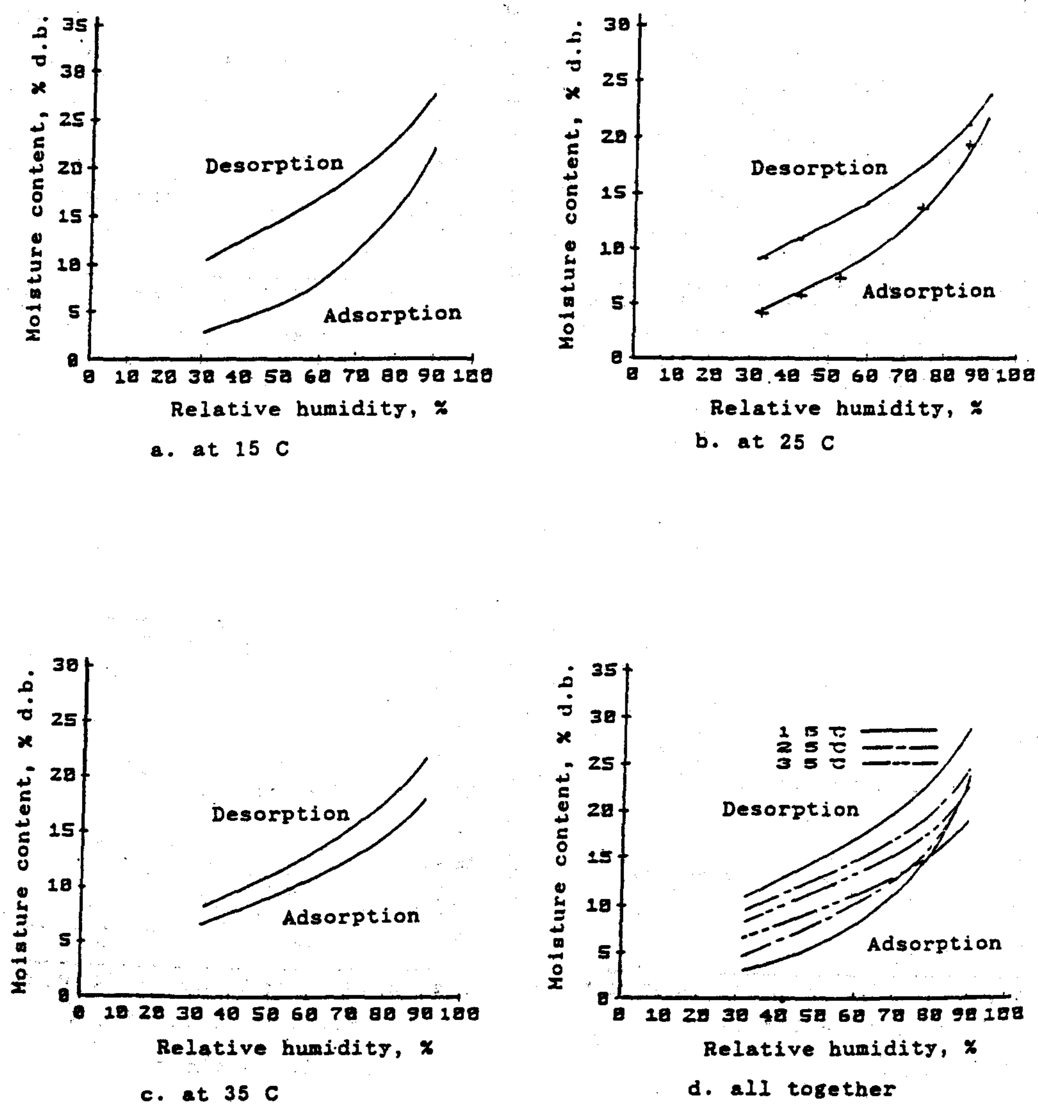


Fig. 5. EMC isotherms of Tainung No. 67 paddy

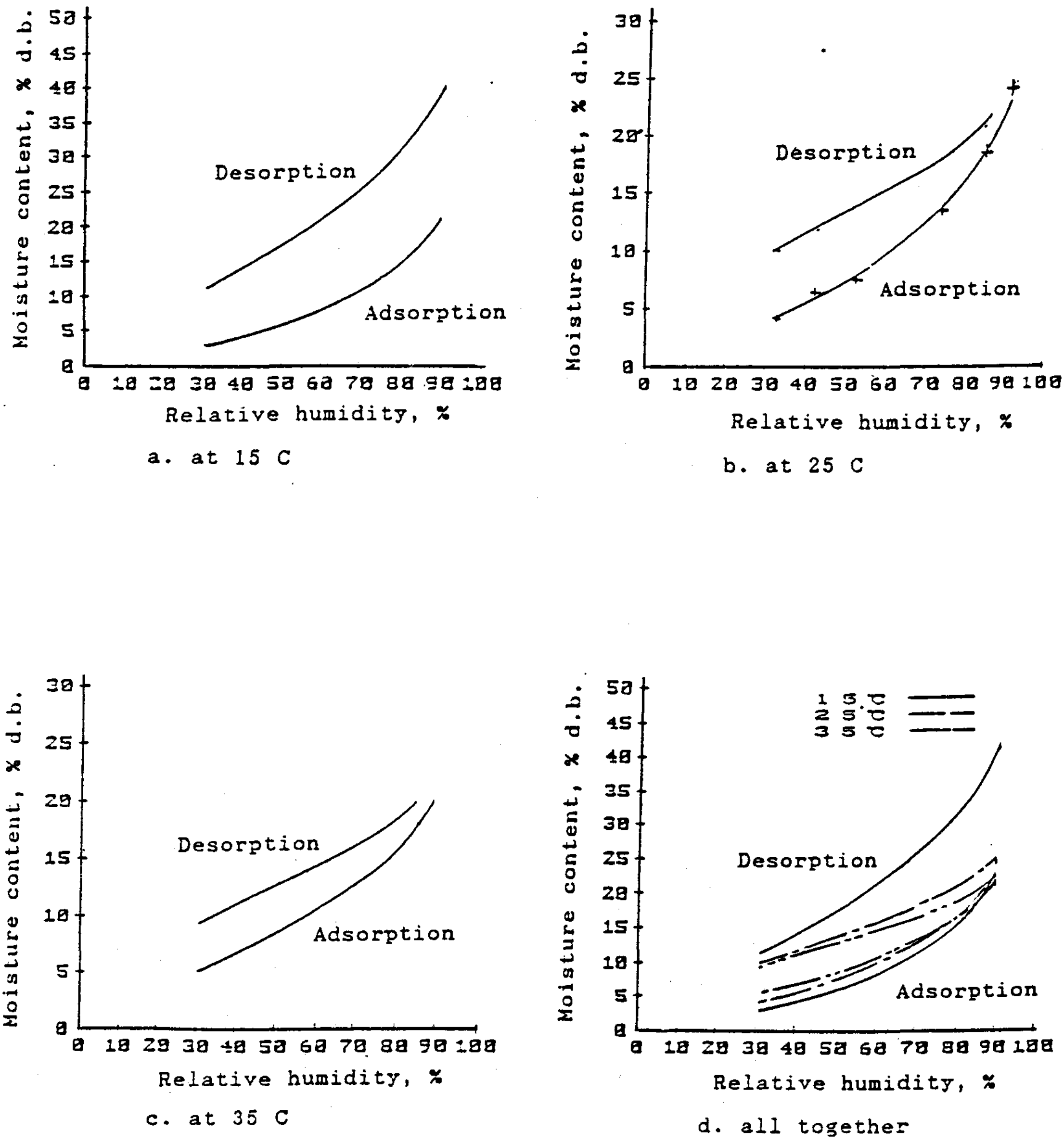


Fig. 6. EMC isotherms of Tainan No. 5 corn

$$1 - (rh/100) = \exp (a M^b)$$

For different temperatures, it is necessary to get different sets of constants a and b.

In regard to local varieties of paddy and corn, it seems that only the desorption EMC isotherms obtained in this study are appropriate for use. For generating adsorption isotherms, more experiments should be conducted in order to get better results.

Further studies may be done on relating EMC model constants a and b with absolute temperature T. If it is successfully developed, then a 3-D EMC model with temperature as the third axis will be very possibly constructed.

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