STATIC PRESSURE DROP IN A FIXED BED OF ROOT CROP CHIPS DURING DRYING AS AFFECTED BY AIRFLOW RATE AND MOISTURE CONTENT

Ramon R. Orias

Philippine Root Crop Research and Training Center (PRCRTC), Visayas State College of Agriculture (ViSCA), Baybay, Leyte 6521-A, Philippines.

ABSTRACT

Orias, R. R. 1991. Static pressure drop in a fixed bed of root crop chips during drying as affected by airflow rate and moisture content. Ann. Trop. Res. 13: 11-26.

Pressure drop (mm H_20/m depth) was generally higher in high-moisture chips than in low-moisture chips. Relationships were found to be normally linear for sweetpotato (*Ipomoea batatas*) and taro (*Colocasia esculenta*) and logarithmically linear for cassava (*Manihot esculenta*). Porosity also increased with moisture, but despite the presence of more void fraction, pressure drop remained high. This was primarily because interspaces in the bed were lined with starch granules and water molecules, thus suppressing the flow of air. When dried, chips decreased in volume and weight and exposed smooth surfaces, thereby causing less resistance to airflow. Among the empirical equations that had been evaluated, the Ramsin and Ergun equations fitted very well with the experimental data. The coefficient of determination, r^2 ranged through 0.94-0.99. The chip's particle diameter was twice larger than that of grains, resulting to lower pressure drop in chips compared to grains such as sorghum (*Sorghum bicolor*), rough rice (*Oryza sativa*), shelled corn (*Zea mays*), and soybean (*Glycine max*).

KEY WORDS: Airflow. Bed porosity. Empirical equations. Moisture content. Root crop chips. Static pressure drop.

INTRODUCTION

The air resistance of the product to be dried is one of the most important values that must be known before designing a drying system or storage facility, particularly on the specification of blower unit. Airflow resistance or pressure drop develops as a result of the energy lost through friction and turbulence. The pressure drop in airflow through any product depends on the rate of airflow, the surface and shape characteristics of the product, the number, size and configuration of the voids, the variability of particle size, and the depth of the product bed.

To date, designers refer to the Shedd curves for pressure drop estimates through empirical relationships between airflow and static pressure drop but others still attempt to formulate theoretical and semi-theoretical studies. Past studies on these aspects for grains and hays have been reviewed and discussed by Brooker *et al.* (1974) and Bakker-Arkema *et al.* (1969). The effects of grain moisture on static pressure drop have also been investigated by Haque *et al.* (1982).

As a nongrain product, root crops vary in most characteristics from food grains. Root crops are living and actively metabolizing plant tissues that continue to respire and transpire at much higher rates than the dry, dormant grains of durable crop products after harvest. As perishable commodities, they are more susceptible to mechanical damage, physiological breakdown and attack by fungi and bacteria. With these differences, an independent study was undertaken to initiate and investigate basic information on the resistance of root crop chips to airflow from fresh to dehydrated form. The study focused on three kinds of root crop chips, namely: cassava, sweetpotato and taro.

MATERIALS AND METHODS

Roots of local varieties of cassava and sweetpotato and corms of taro were obtained fresh and direct from the farmers of Los Baños, Laguna. Unpeeled but thoroughly cleaned roots/corms were chipped mechanically using a pedal-operated chipper developed by the Philippine Root Crop Research and Training Center (PRCRTC). Dried chips are shown in Fig. 1. Bins were loosely filled with chips and maintained at a bed depth of 0.58 m. Air temperature and relative humidity were kept at about 60°C and 40%, respectively. The four levels of chip moisture (wet basis) were: M_1=56-72%, M_2=41-55%, M_3=26-40%, and M_4=11-25%. However, only the actual moisture contents determined by the oven method were considered for the data. The five airflow rates controlled were: Q_1=14.58, Q_2=12.97, Q_3=11.00, Q_4=8.07 and Q_5=6.62 $m^3/min/m^2$.

The experimental set-up used is shown in Fig. 2. Air was forced by an electric motor-driven centrifugal blower and was regulated through the damper in the blower gate. A heat conditioning unit consisting of nichrome

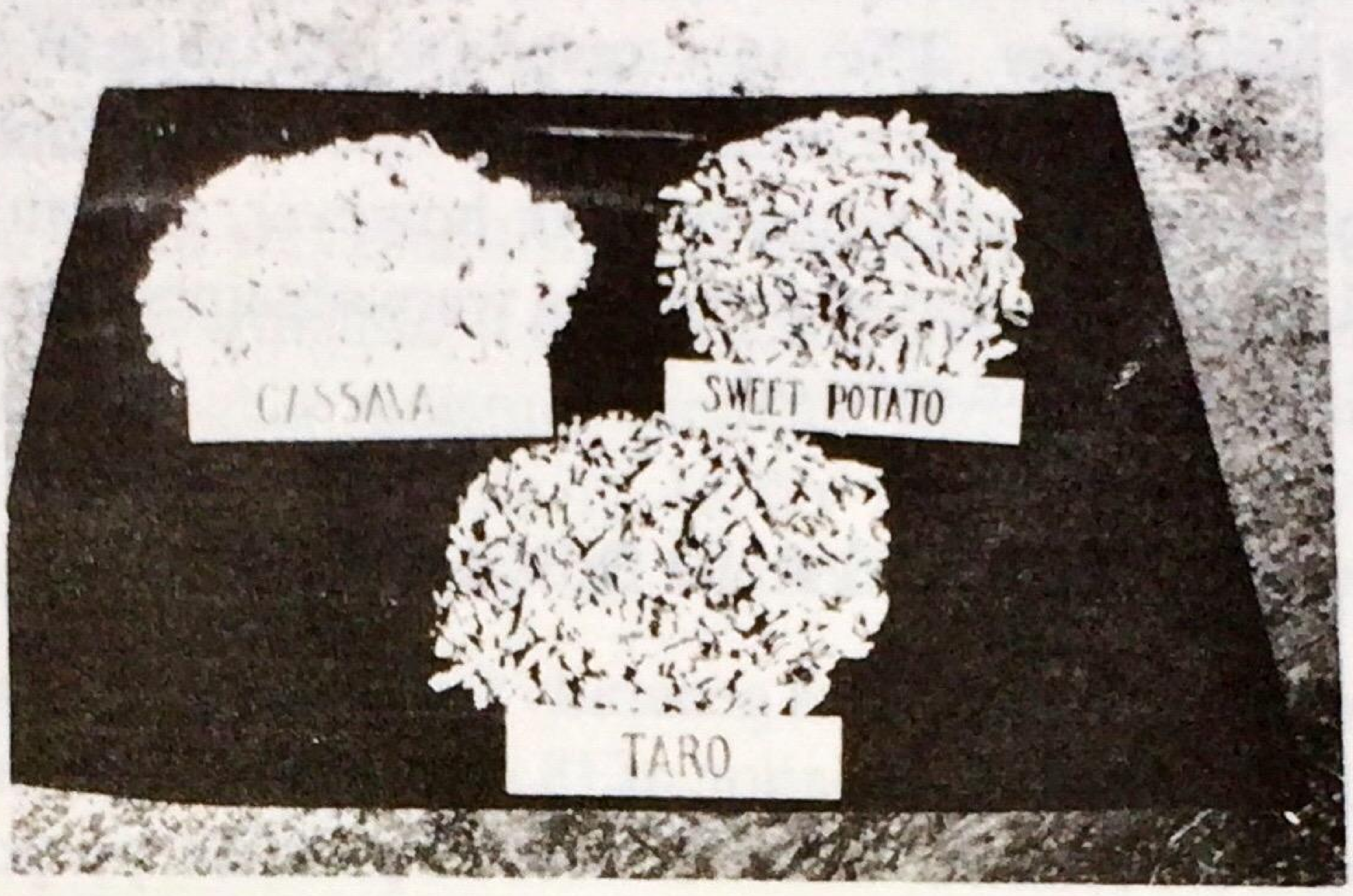

Figure 1. Mechanically produced chips from cassava, sweetpotato and taro, at 13% MC, wb.

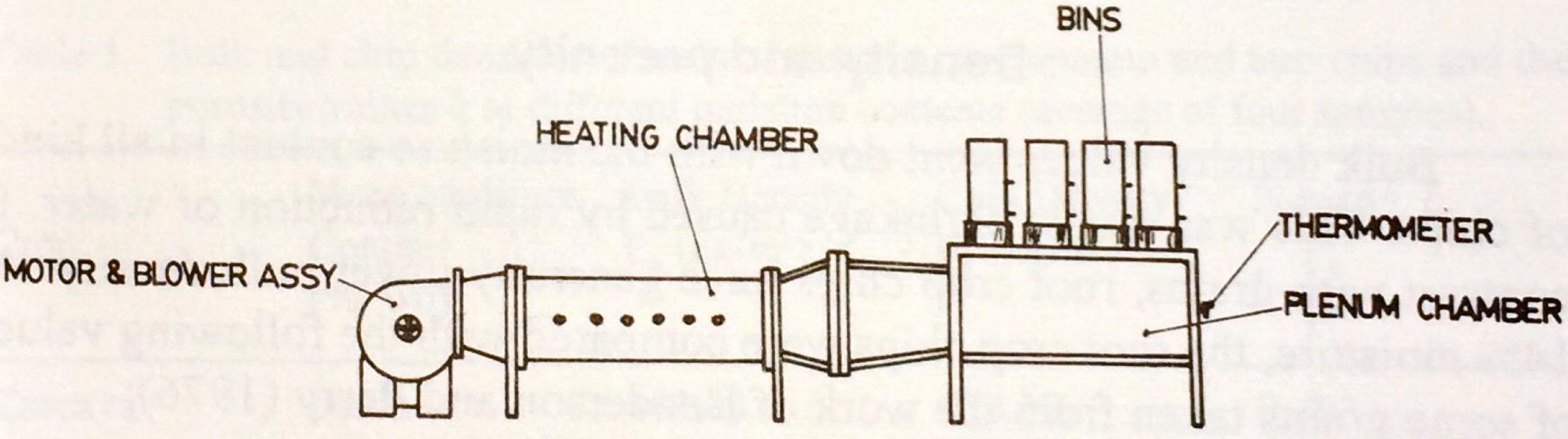

Figure 2. Diagram of the experimental set-up.

wires was corresponded with convenient switches to control air temperature. Pressure drop was determined by direct reading from the Dwyer manometer which was the differential reading of pressures between two vertical points in the bins. The two taps in the bin, about 0.30 m from each other, measured the static pressure in the bed.

The experiment was conducted with the moisture level as the mainplot or the batch-controlled variable. In each batch there were three subplots, the varying rates of airflow. The only response variable in all treatment combinations was the pressure drop in the bin packed with chips. Product bulk and chip densities and porosity were however, determined for each moisture level. Determination of these data were obtained through the bulk-volume water displacement method.

RESULTS AND DISCUSSION

The experimental period was generally fair with mean relative humidity of 70.9% and daily total solar radiation of 18.04 mJ/m^2. Variations of moisture in each test runs were found so small that for all practical purposes, the three tests were considered as three replications. When fresh, taro and sweetpotato have generally more water content (70-73%) than cassava (63%). Starch content analysis for dried chips showed that at 13% moisture (wet basis) cassava, taro and sweetpotato had 81.25, 77.26 and 74.76%, respectively. Non-starchy constituents consisted of fiber, calcium, fats and traces of vitamins.

Density and porosity

Bulk density values went down with the moisture content in all kinds of chips. This was due to shrinkage caused by rapid reduction of water. In contrast with grains, root crop chips have generally lower bulk density. At 14% moisture, the root crop chips were compared with the following values of some grains taken from the work of Henderson and Perry (1976):

Product	**Bulk Density,kg/m^3**
Wheat	770.96
Shelled corn	719.56
Sorghum	642.47
Rough rice	578.22
Sweetpotato	344.83
Gabi	329.72
Cassava	323.03

These values imply that root crop chips are about 50% lighter than grain when dried. Density reduction of chips, i.e. from fresh to dry form (12% M.C.), was 40.62, 37.56 and 31.67%, respectively for cassava, sweetpotato and taro.

No clear trend was established in the bed porosity or void fraction of root crop chips. Nevertheless, it can be noted that greater values of porosities were observed at higher moisture contents, which were about 38.7-41.4% for fresh root conditions (Table 1). In dry form, porosity was about 29.8-30.2%. These levels of porosity fall within the range of the values obtained from grains.

Pressure drop responses

Among the crops tested, cassava provided the highest average pressure drop at 26.02 mm H_20/m depth, followed by sweetpotato at 24.06 mm H_2O/m depth, and taro at 23.57 mm H_2O/m depth. Though no further proof had been pursued, starch content which was found high in cassava chips aptly

Table 1. Bulk and chip densities of beds of cassava, sweetpotato and taro chips and their porosity values ξ at different moisture contents (average of four samples).

Crop	Mean Moisture Content (%, wb)	Bulk Density P_B (kg/m^3)	Chip Density P_T (kg/m^3)	Porosity, ξ $1-\frac{P_B}{P_T}$
Cassava	63.01	463.38	776.17	0.403
	45.48	349.58	521.76	0.330
	28.40	341.83	507.51	0.326
	11.87	323.03	460.84	0.298
Sweetpotato	71.57	470.41	804.04	0.414
	51.31	347.82	524.98	0.338
	31.19	347.34	502.00	0.308
	12.37	344.83	494.13	0.302
Taro	69.97	428.00	699.10	0.387
	50.57	362.05	533.41	0.320
	31.47	345.97	505.26	0.315
	11.33	329.72	477.71	0.309

explained the cause of greater pressure drop. With respect to moisture content, high-moisture chips caused more pressure drop than low-moisture ones. This effect could be attributed mainly to high water content plus the presence of free-starch lining the surface of chips. Starch granules are ruptured through the process of chipping. Porosity was found high in high-moisture chips although it did not facilitate the smooth entry of air since the interspaces in the bed were sealed with films of water and viscous granules. In contrast with grain, pressure drop had been confirmed by past studies to be low when at high-moisture and high as the grains become dry. As reported by Patterson *et al.* (1971) and Haque *et al.* (1982) the increase in pressure drop was attributed to lessening of void fraction or porosity values and the fact that seed coat produces rough surfaces when dried.

The findings on the airflow effects of pressure drop by root crop chips were consistent with the response exhibited by grains. Pressure drop increased in a logarithmic scale with the increase in airflow. The data fitted well with the Ramsin equation (r^2=0.99).

Evaluation of different empirical equations

Mathematical simulations were tried to fit experimental data to existing or published equations. Among the equations evaluated were the Ramsin, Ergun and Haque. The evaluation had satisfactorily undertaken necessary modifications in form and values for practical application in root crop chips.

Ramsin equation

This equation required air condition to be relatively constant. The equation has the following form:

$$\frac{\Delta P}{h} = aQ^b \qquad (1)$$

The constants which are found in Table 2 are recommended only for air temperature around 60°C and relative humidity proximal to 40% during drying. Operating at other range requires reevaluation of the constants, a and b, through experiments. Use values under "right straight lines" when the airflow is above 11 $m^3/min/m^2$ and under "left straight lines" when below it.

Table 2. Values for a and b constants using Ramsin equation[1].

Crop	Moisture Content (%,wb)	Left Straight Lines[2]			Right Straight Line[3]		
		a	b	r^2	a	b	r^2
Cassava	M_1	0.924	1.439	0.999	0.368	1.825	0.999
	M_2	0.814	1.451	0.998	0.339	1.821	0.998
	M_3	0.819	1.434	0.997	0.336	1.814	0.993
	M_4	0.492	1.529	0.999	0.238	1.840	0.987
Sweetpotato							
	M_1	0.880	1.448	0.999	0.562	1.641	0.986
	M_2	0.693	1.505	0.999	0.441	1.697	0.990
	M_3	0.734	1.411	0.997	0.252	1.868	0.982
	M_4	0.433	1.566	0.999	0.240	1.809	0.995
Taro	M_1	0.694	1.539	0.991	0.832	1.470	0.999
	M_2	0.779	1.410	0.996	0.316	1.796	0.990
	M_3	0.756	1.412	0.990	0.337	1.757	0.989
	M_4	0.409	1.618	0.990	0.346	1.692	0.954

[1] Air temperature=60°C; Relative humidity=40%.
[2] Use these values when airflow is below 11 $m^3/min/m^2$.
[3] Use these values when airflow is equal or above 11 $m^3/min/m^2$.

Ergun equation

Reynolds investigation as confirmed by Ergun (1952) showed that the total energy loss in a packed bed was the sum of the viscous and kinetic energy losses. At low airflow rate (laminar flow) the resistance is caused by viscous forces of the air against the product, while at high flow rate (turbulent flow) the contribution of air viscosity in the packed bed becomes negligible compared to the kinetic energy dissipation. These two phenomena became the basis in formulating the original Ergun equation with the following form:

$$\frac{\Delta P}{h} = K_E \, 150 \left[\frac{(1\xi)^2 \; \mu Q}{\xi^3 \; d^2{}_k g_c} + 1.75 \, \frac{(1-\xi) \; \rho Q^2}{\xi_3 \; d_k g_c} \right] \qquad (2)$$

The experimental data on root crop chips were used to evaluate the numerical and literal coefficients of the equation. It was found imperative to adjust some terms based on the physical characteristics of chips such as the following parameters: K_E, Ergun constant; ξ, porosity; and d_K, equivalent diameter. In the first place, equation (2) contains numerical constants as 150 and 1.75 which were derived from the conventional system of units (English). This is definitely not valid for the international system of units (Metric). The transformed version of this in metric system was adopted by Chau *et al.* (1985) with the following form:

$$\frac{\Delta P}{h} = K_1 \frac{(1\xi)^2\, \mu Q}{\xi^3\, d^2_k g_c} + K_2 \frac{(1-\xi)\, \rho Q^2}{\xi^3\, d_k g_c} \qquad (3)$$

or

$$\frac{\Delta P}{h} = K_1 MQ + K_2 NQ^2 \qquad (3a)$$

where:

$$M = \frac{(1-\xi)^2}{\xi^3} \frac{\mu}{d^2_k g_c} \qquad (3b)$$

$$N = \frac{1-\xi}{\xi^3} \frac{\rho}{d_k g_c} \qquad (3c)$$

$$\xi = b \sqrt{\frac{P_B}{a}} \qquad (3d)$$

Calculated values of M and N parameters are shown in Table 3 for various moisture levels and certain condition of drying air. Any changes in air viscosity and density can be dealt with the adjustments in M and N parameters. In contrast with Ramsin equation, there is no need to reevaluate through experiments the whole constants in Ergun equation.

Table 3. Equivalent diameter of chips, porosity values, and the numerical coefficients in the Ergun equation determined from each moisture level (equation 3a).

Moisture Level (%, wb)	Porosity ξ	Equivalent Diameter d_k(m)	M (x 10^{-5})	N (x 10^{-2})	K_1	K_2	r^2
Cassava							
63.01	0.403	0.0110	2.43	2.39	43,970	6.41	0.987
45.48	0.330	0.0109	6.32	5.40	14,663	2.65	0.986
28.40	0.326	0.0109	6.78	5.75	13,345	2.42	0.978
11.87	0.298	0.0109	8.09	6.72	6,887	1.72	0.982
Sweetpotato							
71.57	0.414	0.0111	1.99	2.05	57,632	6.61	0.981
51.31	0.338	0.0110	7.12	6.04	13,026	2.17	0.987
31.19	0.308	0.0109	7.29	6.13	10,257	1.99	0.960
12.37	0.302	0.0109	7.50	6.28	7,521	1.65	0.991
Taro							
69.97	0.387	0.0105	3.40	3.07	32,168	4.18	0.983
50.57	0.320	0.0102	6.88	5.54	12,373	2.19	0.971
31.47	0.315	0.0101	8.30	6.49	10,476	1.75	0.977
11.33	0.309	0.0100	10.10	7.66	6,004	1.44	0.942

Standard conditions:
T = 60°C
RH = 40%
μ = 2.0 x 10^{-5} kg/m-sec
ñ = 1.059 kg/m^3

r^2, test of significance:
5% : 0.878
1% : 0.959
n : 5, df = 3

Haque equation

The pressure drop data has been defined in Ramsin equation as a function of airflow alone and in Ergun equation as a function of bed porosity, air viscosity, density and velocity. These equations obtained numerous constants that may eventually lead to faulty calculations and are thus inconvenient for practical use. By analysis the trend in data and the plotted curves appeared that pressure drop involves a linear regression of the first order with moisture and a linear and a second order terms in airflow. A statistical non-linear regression model was used to fit the pressure drop data. The model originally adopted by Haque *et al.* (1982) for corn, sorghum and wheat, consisted both the airflow (Q) and moisture content (M) variables as indicated in the following form:

$$\frac{\Delta P}{h} = aQ + bQ^2 - cMQ \tag{4}$$

The regression analysis of the experimental results using equation 4 showed that at least one variable in the equation remained not significant with the variation in pressure drop. This meant there is a need to either eliminate or modify one term. It may be recalled that in most grains where equation 4 is most applicable the moisture content varies conversely with pressure drop, in which case opposite relationship occurred in root crop chips. Therefore, by judicious consideration, equation 4 has been modified in the following form:

$$\frac{\Delta P}{h} = aQ + bQ^2 - c\,\frac{Q}{M} \tag{5}$$

This new model fits very well the data of chips with a coefficient of determination (r^2)=0.99. Values for the constants of regression are found in Table 4.

Table 4. Values of the constant a, b and c in the new statistical model used to fit pressur drop data of root crop chips (equation 5).

Crop	a	b	c	r^{2*}
Cassava	1.317	0.143	13.095	0.998
Sweetpotato	1.294	0.125	12.781	0.996
Taro	1.152	0.118	7.662	0.996

*Highly significant at 1% level (n = 20).

The estimated pressure drop values by different equations together with the experimental results were compared through graphical projections. The curves described by the results are shown in Fig 3-5 for each crop. All the simulated equations established similar trends and shapes of curves with the experimental result, except for some minimal deviations by some equations. Both the Ramsin and Ergun estimates nearly coincided with the experimental data in all moisture levels. In the case of Haque equations pressure drop estimates were generally lowered at M_1 (63-72% M.C.) in all crops. Hence, Haque equation is applicable only for moisture contents below 51%. However, for convenience and speedy means of predicting pressure drop values, Haque equation is most acceptable than the Ramsin and Ergun equations.

Comparison with other crops in Shedd diagram

The pressure drop data of chips were superimposed on the Shedd diagram including only important crops such as soybeans, shelled corn, rough rice and grain sorghum. Fig 6 clearly shows the relative pressure drop response of root crop chips as compared to grains. In general, dried grains have higher pressure drop than root crop chips in both dry and fresh forms except for fresh chips which have a slightly higher pressure drop than soybeans.

Moreover, the particle equivalent diameter factor has a substantial effect on the resistance to airflow, *i.e.* smaller grains like sorghum provide higher pressure drop than larger grains. For chips, the equivalent particle diameter was about 11 mm higher than those of grains like sorghum (3 mm), rough rice (5 mm), soybeans, and shelled corn (8 mm) (Matthies and Petersen, 1974). Chips were also consistent with grains in terms of the rate of change of pressure drop per unit change in airflow rate since the curves run almost parallel with each other.

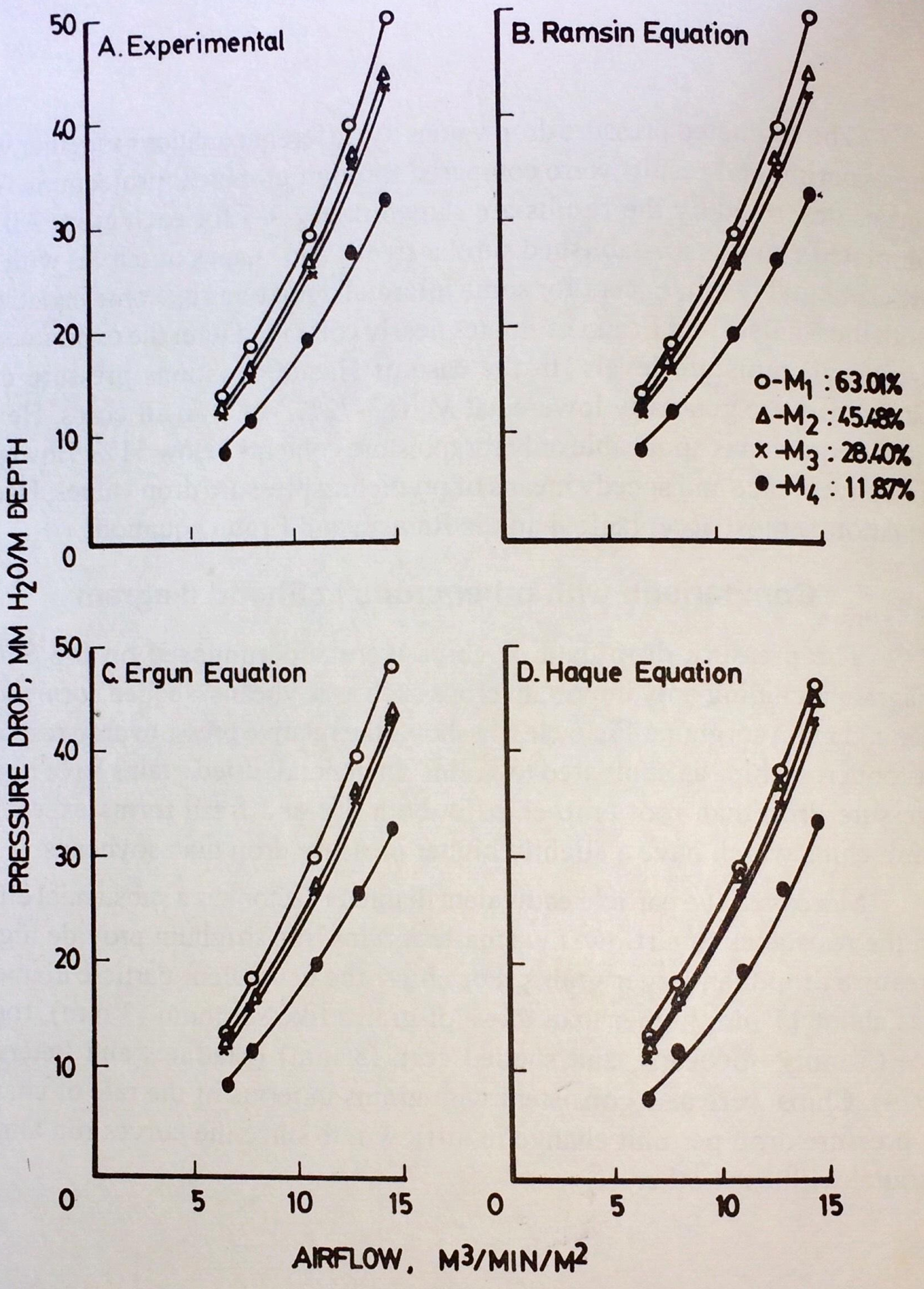

Figure 3. Pressure drop curves in cassava chips at different moisture levels based experimental results (A), Ramsin equation (B), Ergun equation (C), and Haqu equation (D).

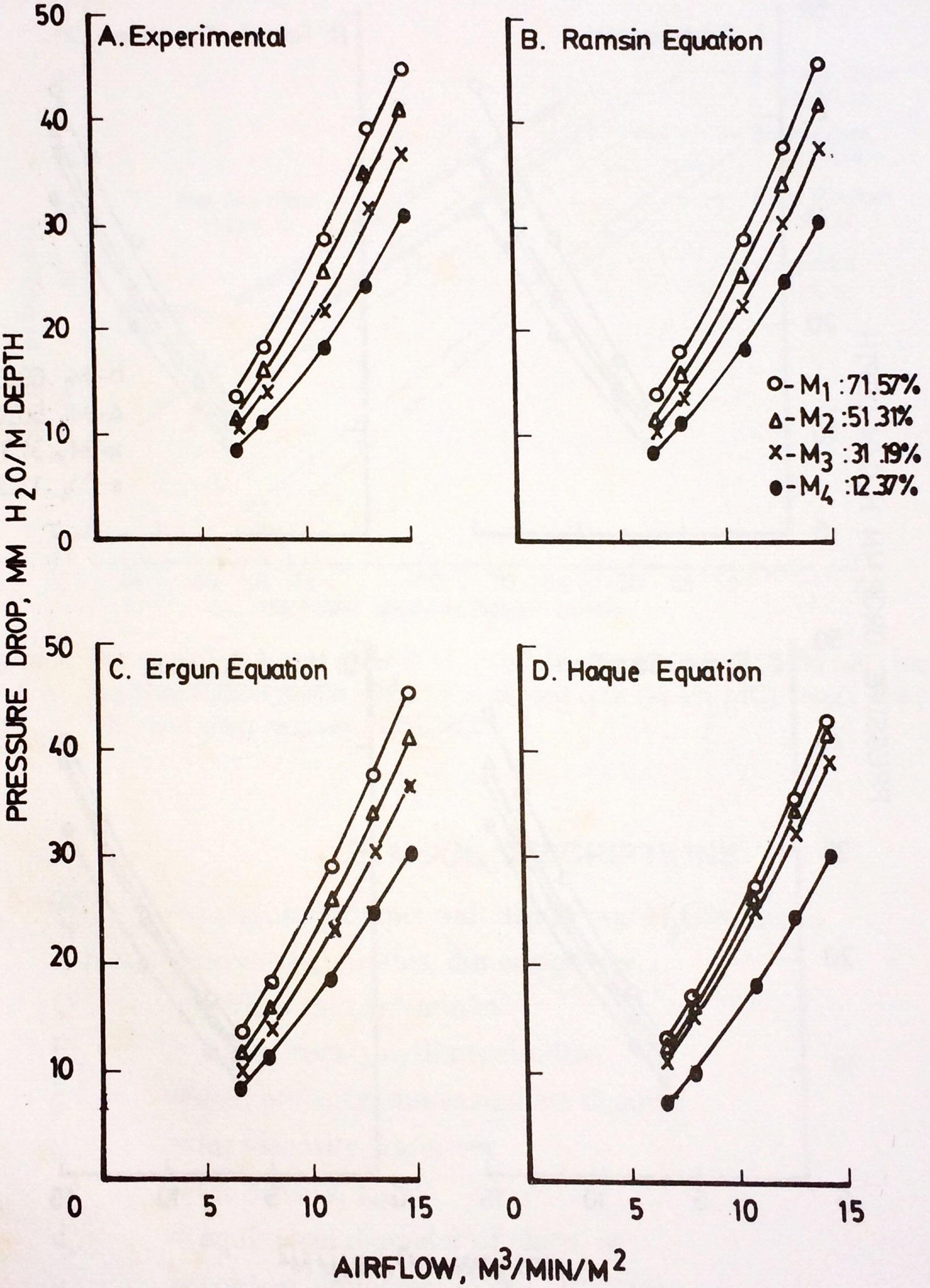

Figure 4. Pressure drop curves in sweetpotato chips at different moisture levels based on experimental results (A), Ramsin equation (B), Ergun equation (C), and Haque equation (D).

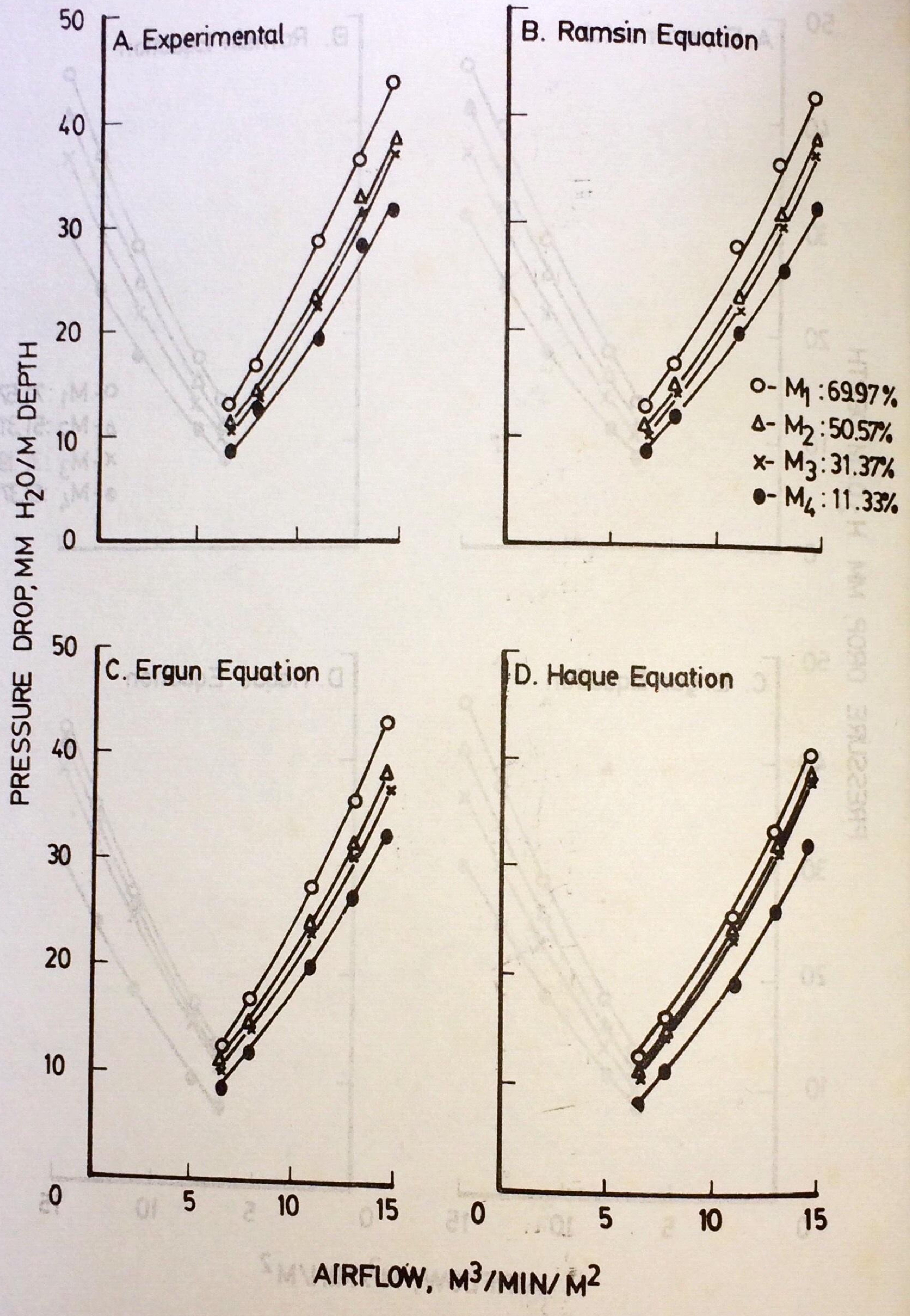

Figure 5. Pressure drop curves in taro chips at different moisture levels based o experimental results (A), Ramsin equation (B), Ergun equation (C), and Haqu equation (D).

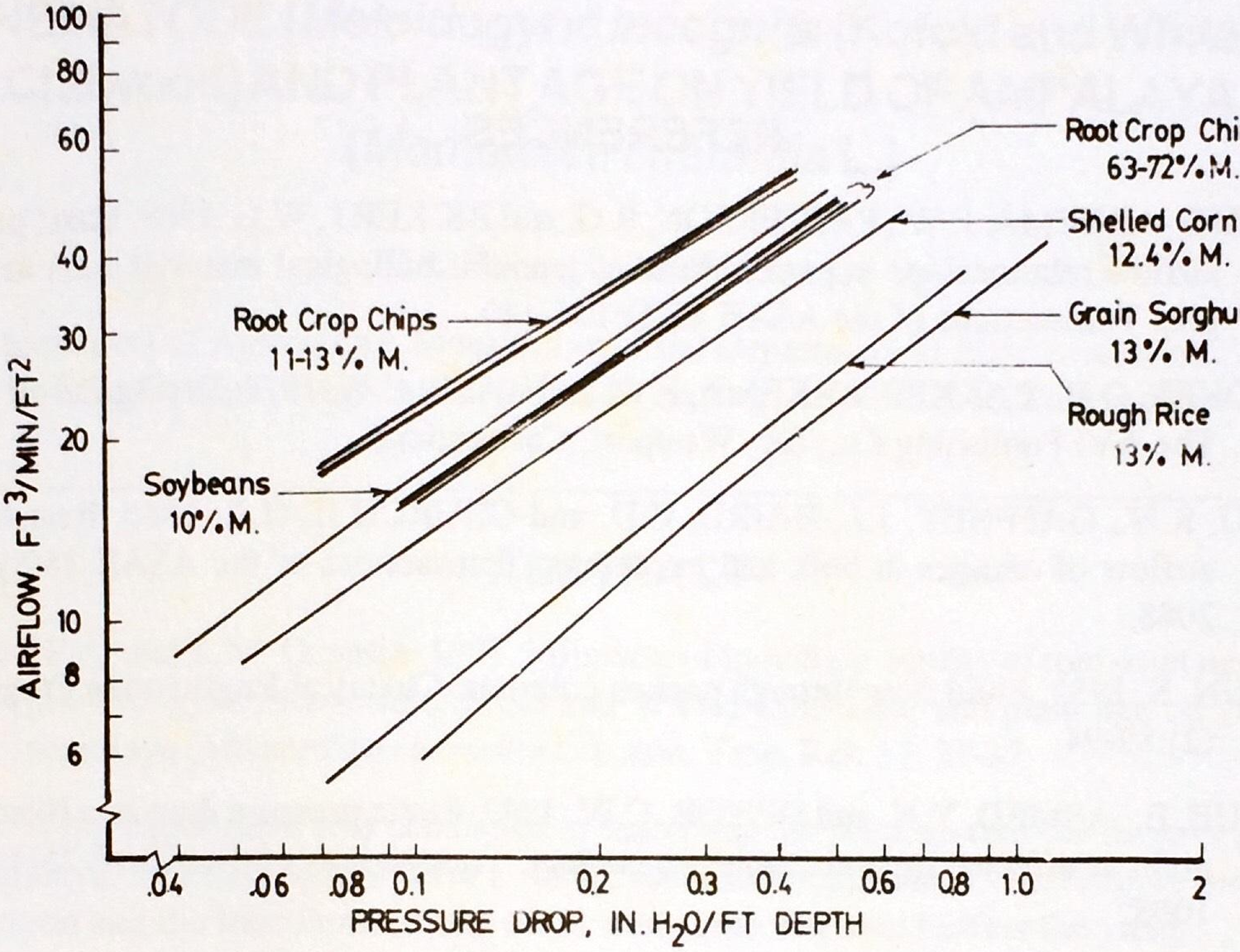

Figure 6. Pressure of root crop chips at M_1 (63-72% MC) and M_4 (11-13% MC) plotted together with soybeans (10% MC), shelled corn (12.4% MC), rough rice (13% MC) and grain sorghum (13% MC).

SYMBOL DESCRIPTIONS

$\frac{\Delta P}{h}$ = pressure drop per unit depth, mm H_2O/m depth

a, b & c = product constants, dimensionless

Q = airflow rate, m^3/min/m^2

K_E = Ergun constant, dimensionless

ξ = Bed porosity, dimensionless decimal

μ = air viscosity, kg/m-sec

ρ = air density, kg/m^3

d_k = equivalent diameter of chips, m

g_c = conversion factor, 35280 $\frac{\text{Pa-Sec}^2}{\text{min}^2\text{mm H}_2\text{0}}$

P_B = product bulk density, kg/m^3

P_T = absolute chip density, kg/m^3

REFERENCES

BAKKER-ARKEMA, F.W., PATTERSON, R.G. and BICKERT, W.G. 1969. Static pressure-airflow relationships in packed beds of granular biological material such as cherry pits. Transactions of the ASAE 12(1):134-140.

BROOKER, D.B., BAKKER-ARKEMA, F.W. and HALL, C.W. 1974. Drying Cereal Grains. The AVI Publishing Co., Inc. Westport, Connecticut.

CHAU, K.V., GAFFNEY, J.J., BAIRD, C.D. and CHURCH II, G.A. 1985. Resistance to airflow of oranges in bulk and in cartons. Transactions of the ASAE 28(6):2083-2088.

ERGUN, S. 1952. Fluid flow through packed columns. Chemical Engineering Progress 48 (2):89-94.

HAQUE, E., ASMED, Y.N. and DEYOE, C.W. 1982. Static pressure drop in a fixed bed of grain as affected by grain moisture content. Transactions of the ASAE 25(4):1095-1098.

HENDERSON, S.M. and PERRY, R.L. 1976. Agricultural Process Engineering. 3rd ed. The AVI Publishing Co., Inc. Westport, Connecticut.

MATTHIES, H.J. and PETERSEN, H. 1974. New data for calculating the resistance to airflow of stored granular materials. Transactions of the ASAE 17(6):1144-1149.

PATTERSON, R.J., BAKKER-ARKEMA, F.W. and BICKERT, W.G. 1971. Static pressure-airflow relationships in packed beds of granular biological materials such as grains. Transactions of the ASAE 14(1):172-174.