RESISTANCE TO AIRFLOW THROUGH SWEET POTATO AERIAL VINE COMPONENTS

J. K. Korese, O. Hensel

ABSTRACT. *Designers of forced air handling systems require data on resistance to airflow for accurate selection of fans and mathematical prediction of pressure drop and airflow patterns. In this research, resistance to airflow of sweet potato leaves and chopped sweet potato aerial vines dried in an experimental cabinet dryer was measured to determine the effect of airflow rate, moisture content and bulk depth. Five levels of moisture contents (88.7%, 74.7%, 52.9%, 26.8%, and 11.0% w.b.) for sweet potato leaves and (88.1%, 69.1%, 52.2%, 35.0%, and 12.2% w.b.) for chopped sweet potato aerial vines, respectively, and four levels of bulk depths (0.30, 0.45, 0.60, and 0.75 m) were investigated at airflow rates ranging from 0.0206 to 0.2342* $m^3\ s^{-1}\ m^{-2}$*. Results indicated that airflow, moisture content, and bulk depth have significant (*$P < 0.01$*) effect on airflow resistance of sweet potato leaves and chopped sweet potato aerial vines. Equations that relate pressure drop to airflow rate, moisture content, and bulk depth were developed based on the Hukill and Ives (1955) equation through the implementation of empirical "de-rating" factors and the coefficients obtained by regression analysis. The developed models provided a good fit to the experimental pressure drop data obtained in the range of conditions investigated. Also, comparison of the pressure drop data in this study with marigold flowers cited in the literature shows that the resistance to airflow for both sweet potato leaves and chopped sweet potato aerial vines was lower than that of marigold flowers. The pressure drop curves for sweet potato leaves however had a steeper slope than the marigold flowers. Bulk density which varied from 29.57 to 112.63 kg* m^{-3} *for sweet potato leaves and 83.99 to 317.23 kg* m^{-3} *for chopped sweet potato aerial vines was significantly affected by moisture content.*

Keywords. *Bulk depth, Bulk density, Chopped aerial vines, Curves, Leaves, Moisture content, Sweet potato.*

Sweet potato (*Ipomoea batatas* L.) is an important food and feed crop in most developing countries because of its nutritional advantages. The tops of sweet potato plants can be continuously harvested over many months, not just once like many other commercial vegetables or forage crops. The aerial vines of the plant are rich in polyphenols such as caffeic acid, chlorogenic acid, and other caffeoylquinic acid derivatives, as well as many nutrients including protein, dietary fiber, carotenoids (carotenes and xanthophylls), vitamins, and minerals (Ishida et al., 2000; Sugiura and Watanabe, 2011). It has been documented that the aerial vines of the plant can be used as a direct feed or as a feed supplement for animals (Brown and Chavalimu, 1985; Teguia et al., 1997; Farrell et al., 2000). Carotene and xanthophyll is used in the poultry industry as a feed supplement for the coloration of egg yolks and chicken skin. As an alternative, sweet potato aerial vine components could be used to enhance the yellow color produced in the skin and yolk of broilers or for other domestic and industrial applications. Sugiura and Watanabe (2011) reported that great amounts of sweet potato aerial vines are produced as a by-product after harvesting of the roots. Most of these are however discarded in the current sweet potato production systems in tropical and subtropical climates where it is mostly cultivated. It is therefore anticipated that if the aerial parts of sweet potato plants are collected and preserved, local farmers can earn additional revenue.

The leaves and stems of sweet potato have high moisture content and are perishable (Sugiura and Watanabe, 2011). Since they have a short shelf-life, they must be processed or preserved for future processing or for use as a functional animal feed. One of the methods of preservation is to dry the plant parts by forcing heated air through them to remove moisture (Janjai and Tung, 2005; Müller and Heindl, 2006). Due to the variety of agricultural products, namely leaves, stems, flowers, roots and fruits of food/feed, herbal and medicinal plants, dryers of different designs exist and are often configured to specific needs (Müller and Heindl, 2006). For instance, many of the plants are heat sensitive and tend to loose quality during drying. As a result, dryer designs must conform to the plant parts to be dried. This implies that drying must be carried out under specific conditions in order to obtain the desired final product quality. To carry out drying, harvested products are

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usually bulked up on a grated floor of a dryer and dried by forcing heated air through the product using ventilators. During this phase, there will be gradients for moisture content, temperature, and relative humidity as a function of bulk height, which changes as drying progresses. The drying time depends mostly on the bulk height, air velocity, and the applied temperature and relative humidity of the inlet air. Therefore, for the operation of such drying systems several decision variables must be taken into account. For instance, airflow can be reduced to decrease the pressure head and the power required to operate a dryer ventilator. Moreover, a commercial dryer should be monitored continuously to adjust the fan speed and airflow direction to achieve the right moisture content efficiently without over-drying (Iqbal et al., 2015). High moisture content and smaller particle size result in higher bulk density, which increases the pressure drop across the drying plenum. High airflow speed also increases the pressure drop due to more resistance of the material. Therefore, airflow through bulk products during drying provides a means of environmental control for the chemical changes likely to occur as well as moisture removal. To optimally design a forced air ventilation system for drying bulk aerial vines of sweet potato, the resistance to airflow data is required and must be estimated realistically in order to appropriately match a fan to the drying system and its content.

A number of research workers have studied airflow resistance of various biological products, ranging from woody biomass (Suggs and Lanier, 1985; Kristensen and Kofman, 2000; Sadaka et al., 2002; Grubecki, 2015; Iqbal et al., 2015) to milkweed pod (Jones and Von Bargen, 1992). Pressure drop data for more common products like grains and seeds, as well as other agricultural products, have also been documented in ASABE standard D272.3 (*ASABE Standards*, 2011). To determine airflow relationships for a biological material, it is common to include some physical characteristics of the material (Gunasekaran and Jackson, 1988; Li and Sokhansanj, 1994; Reed at al., 2001). Cooper and Sumner (1985) reported that biomass pressure drop characteristics are often affected by bulk density and particle size. For example, bulk density, moisture content, particle size, and shape were shown to influence the pressure drop curves for chopped miscanthus and alfalfa leaves (Rabe and Currence, 1975; Iqbal et al., 2015) and density and leaf orientation were the determining parameters for pressure drop in fresh tobacco leaves (Suggs et al., 1985; Anderson et al., 1998). For whole potatoes, Irvine et al. (1993) reported that pressure drop was affected by potato size and airflow direction for different potato types while airflow resistance in sugar beet roots was influenced by root size and presence of foreign materials (Tabil et al., 2003). To date, limited data on the resistance to airflow of sweet potato leaves and chopped sweet potato aerial vines have been reported in literature or compiled in ASABE standard D272.3 (*ASABE Standards*, 2011), which presents resistance to airflow for about 40 agricultural commodities. Considering that the cost of acquisition and operation of ventilation fan are related to its power which is a function of airflow and static pressure to be supplied, it is important to understand the factors that influence its power demand.

The objectives of this study were: (1) to measure and evaluate the pressure drop as a function of airflow through bulk sweet potato leaves and chopped sweet potato aerial vines at different moisture contents and bulk depths, (2) to establish the relationship between bulk density and bulk depths at different moisture contents, and (3) to develop model equations based on the experimental data to predict pressure drop across bulk sweet potato leaves and chopped sweet potato aerial vines for a range of drying conditions.

MATERIALS AND METHODS

PLANT MATERIAL

Sweet potatoes (*Ipomoea batatas* L. cv. CRI-Apomuden) used in this study were grown in summer 2014 at the Experimental and Demonstration farm of the Department of Agricultural Engineering, University of Kassel, Witzenhausen, Germany. The sweet potatoes were grown according to organic production practices and the aerial vines were harvested before flowering. Figure 1 shows a sweet potato plant and its major components. Two different samples were investigated in this study: sweet potato leaves and chopped sweet potato aerial vines. The leaves, here refers to the sweet potato aerial vine components formed by a single leaf and a petiole. For each sample, the matured aerial vine components were randomly harvested by hand in early morning to avoid shrinkage due to environmental drying. After harvesting, the samples were immediately transported to the research laboratory. The leaves were manually separated from the vines. The entire aerial vines of the plants were also collected and chopped into particles of between 1.5 to 3.0 cm long pieces using a straw cutting machine (FLORICA E-1800, Germany). The mixture of the leaves and the stem material (petiole and stem) was 24.6% and 75.4% by weight, respectively. Almost all experiments were performed within one or a maximum of two days and consisted of several experimental measurements.

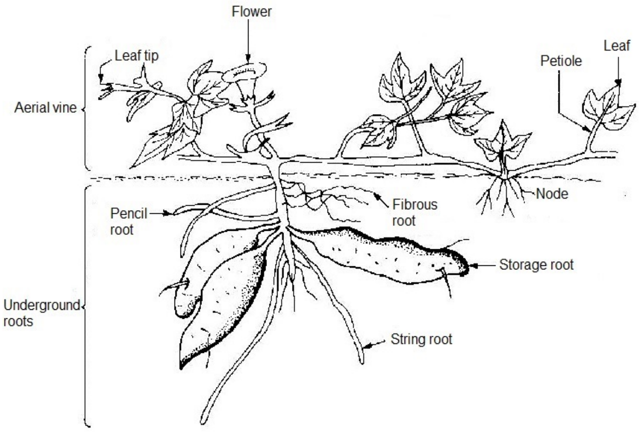

Figure 1. A drawing showing the morphology of a sweet potato plant (Woolfe, 1992). In practice, the proportion of foliage to root is somewhat greater than that shown here.

TEST EQUIPMENT

The arrangement of the apparatus used for the study was similar in dimensions (except the test chamber), though not necessarily in concept, to that used by Román and Hensel (2014) and is shown in figure 2. The main parts of the apparatus are air inlet duct, butterfly valve, centrifugal in-line duct fan (type KRW315/4F, Helios Ventilatoren, Germany), air plenum, and test chamber. The entrance to the apparatus consisted of a round galvanized steel air duct with a diameter of 0.15 m and a length of 0.85 m. At 0.3 m downstream from the duct inlet, a honeycomb flow straightener with tube diameter of 0.005 m and tube length of 0.05 m was installed to remove any tangential velocity components. The butterfly valve was installed immediately upstream of the fan in order to reduce the airflow to the desired test conditions. Below the perforated plate which formed the bottom of the test chamber, three additional perforated plates with a space of 0.05 m between them were installed to improve the flow uniformity after the change of direction in the plenum chamber. The test chamber consisted of a cylindrical container constructed from transparent acrylic material of 1 m long and 0.45 m internal diameter.

Hot wire anemometer (Airflow TA-5, Airflow Lufttechnik GmbH, Germany) was inserted through a port located at the duct center and 0.4 m downstream of the flow straightener to measure the air velocity profile. To determine the airflow rate in the system, the guideline of VDI/VDE 2640 part 3 (1983) was used as detailed by Román and Hensel (2014). Static pressure was measured across bulk sweet potato aerial vine components using an electronic differential pressure meter (Testo 510, Testo AG, Germany). The device was connected to four pressure tabs by a flexible rubber tubing located immediately below the test chamber base.

PRESSURE DROP TEST

Measurements of pressure drop were obtained for sweet potato leaves and chopped sweet potato aerial vines at various moisture contents and bulk depths. To obtain samples of different moisture content conditions, sweet potato leaves and sweet potato aerial vines were dried in a laboratory cabinet dryer. The cabinet dryer consisted of 24 square-shaped trays which were stacked on a rack at 0.1 m intervals. Each tray had a drying area of 0.308 m^2. The trays of the dryer were loaded with approximately 0.03 m thickness of drying material in order to ensure uniform drying. The drying air temperature during samples drying was set at 60°C for all experiments in order to reduce the drying time (Sugiura and Watanabe, 2011). Nevertheless, adjusting the drying air temperature from 60°C to 36°C is reported to improve the polyphenol content of dried sweet potato leaves (Sugiura and Watanabe, 2011). For a given experimental material, the samples were dried for a couple of hours (table 1), removed, and placed in the airflow resistance measurement system (fig. 2). After each measurement, the samples were placed back in the cabinet dryer for additional drying and the same sequence of pressure drop measurement repeated as reported by Reed et al. (2001). The duration required to obtain a given moisture content condition was based on preliminary drying test that were conducted. Drying experiments were performed once for each moisture condition.

Pressure drop measurements for each test condition were conducted as follows. The test chamber was filled manually with non-compacted material to a desired depth. Once the chamber was filled, the fan was switched on. Then the pressure drop was measured by throttling the fan at predetermined series of increasing airflow rates, from

Table 1. Sweet potato aerial vine components moisture contents and test depths for pressure drop measurements during drying at 60°C.

Test Depths (m)	Drying Interval (hr)	Leaves MC (% w.b.)	Chopped Aerial Vines MC (% w.b.)
0.30, 0.45, 0.60, 0.75	0[a]	87.7	88.1
	2.2	74.7	69.1
	4.2	52.9	52.2
	6.2	26.8	35.0
	7.2	11.0	12.2

[a] Fresh samples

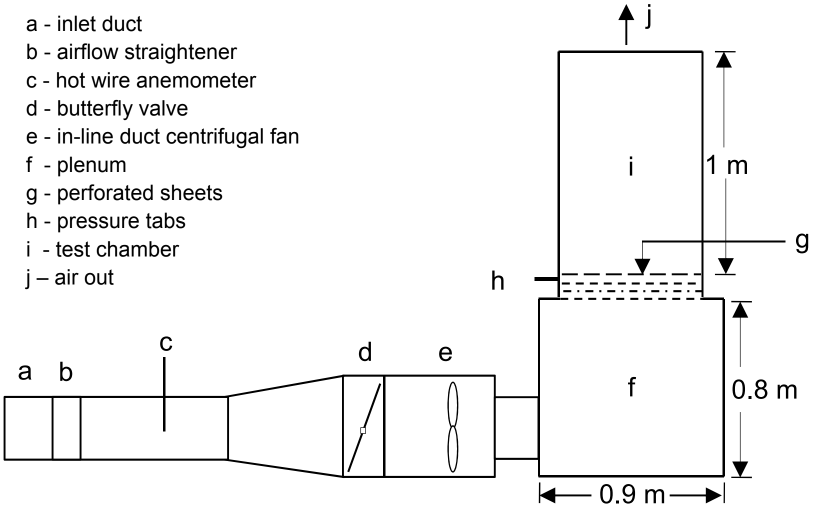

Figure 2. Schematic diagram of the apparatus used for airflow resistance measurement.

0.0206 to 0.2342 $m^3\ s^{-1}\ m^{-2}$. Three replications were performed for a given moisture content and depth, and a randomized approach was used for the sequencing of test within each experiment. Although it was not possible to keep the moisture contents as desired due to the handling and test runs, moisture differences were not significant in all cases. The bulk density of the material was obtained by dividing the mass required to fill a given depth of the chamber by its volume. Moisture content of the test material after each drying phase was determined in triplicate according to ASABE S358.3 (*ASABE Standards,* 2012). Due to shrinkage during the drying phase, the maximum bulk depth that could be tested decreased at moisture content levels of 52.9% to 11.0% w.b. for leaves and 52.2% to 12.2% w.b. for chopped aerial vines. As a result, additional drying tests were performed and combined with previously dried material to create enough volume for testing. The drying interval, moisture contents, and bulk depths are presented in table 1.

ANALYSIS OF AIRFLOW RESISTANCE DATA

Several models have been used to describe the relationship between airflow and pressure drop data, including Shedd (1953) equation, Hukill and Ives (1955) equation, and the Ergun (1952) equation. The Hukill and Ives (1955) equation was selected as an ASABE standard (*ASABE Standards*, 2011) and is used to represent a wide range of materials. Therefore, the airflow resistance results for each data of fixed moisture content and bulk depth were fitted into the Hukill and Ives (1955) equation:

$$\frac{\Delta P}{L} = \frac{aV^2}{Log_e\left(1+bV\right)} \qquad (1)$$

where

ΔP = pressure drop (Pa),

L = bulk depth (m),

V = airflow ($m^3\ s^{-1}\ m^{-2}$),

a and *b* = constants for a particular material (regression coefficients).

The model constants of equation 1 were estimated by fitting the model to the experimental data by non-linear regression using the statistical analysis program, IBM SPSS Statistics 22. The effect of different variables (airflow, moisture content, and bulk depth) on the resistance to airflow of bulk sweet potato leaves and chopped sweet potato aerial vines were determined using completely randomized design (CRD) method with three replications. The data were analyzed using univariate analysis of variance (ANOVA) in SPSS. Pressure drop was treated as the depended variable.

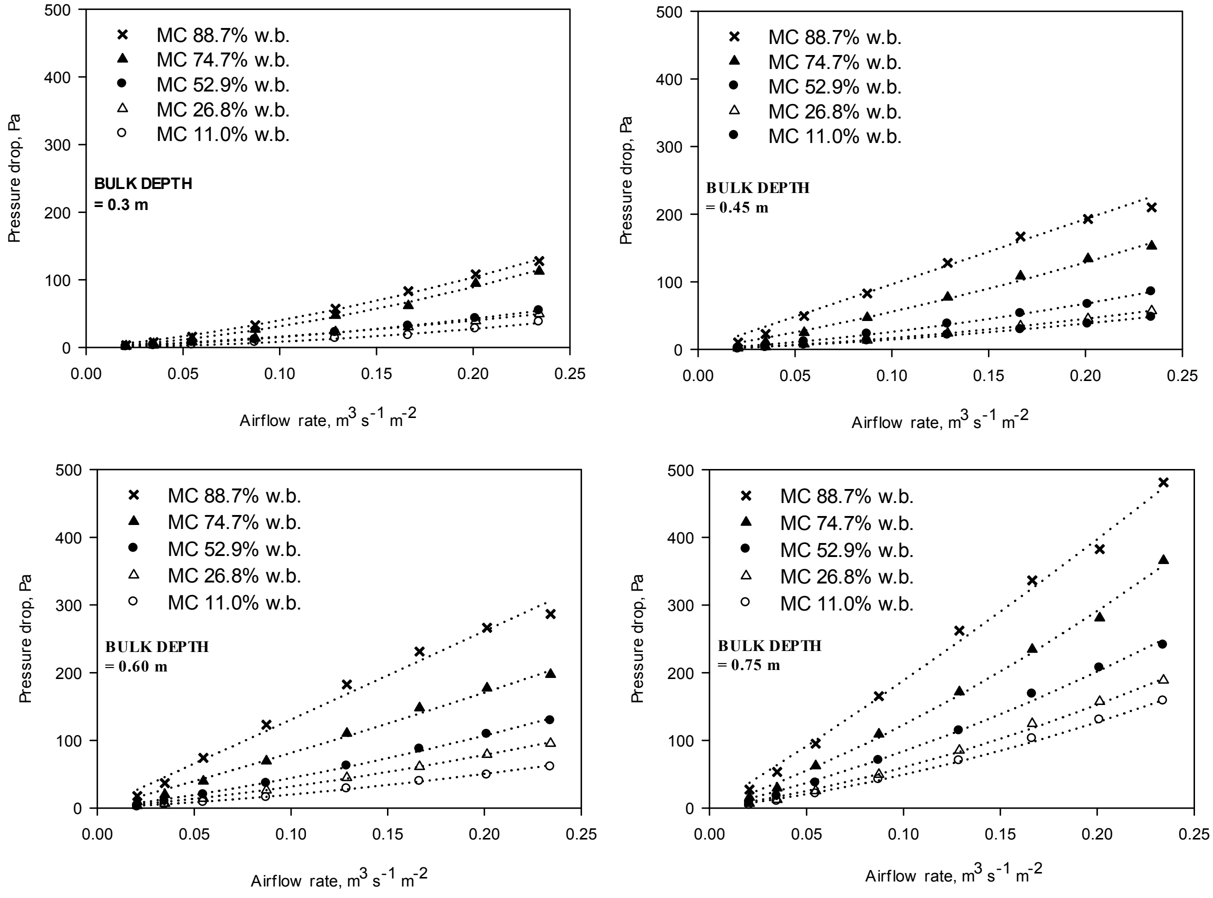

Figure 3. Relationship between pressure drop and airflow for sweet potato leaves at different moisture contents and bulk depths.

RESULTS AND DISCUSSION

RESISTANCE TO AIRFLOW

A laboratory test stand was used to determine the resistance to airflow through sweet potato leaves and chopped sweet potato aerial vines over airflow rate range of 0.0206 to 0.2342 $m^3 s^{-1} m^{-2}$. The pressure drop across the empty test chamber of the test stand was found as 0.66 to 44.74 Pa for airflow rates ranging from 0.0206 to 0.3095 $m^3 s^{-1} m^{-2}$. To evaluate the pressure drop due to the sweet potato leaves and chopped sweet potato aerial vines only, the pressure drop values of the empty test chamber were subtracted from the pressure drop measurements for the chamber with sweet potato leaves and/or chopped sweet potato aerial vines at similar velocities. Figures 3 and 4 exemplify pressure drop data of sweet potato leaves and chopped sweet potato aerial vines in the moisture content range of 88.7% to 11.0% w.b. and 88.1% to 12.2% w.b., respectively, and for bulk depths of 0.30, 0.45, 0.60, and 0.75 m. The dotted lines in all the figures are model fitting results based on an empirical modification of Hukill and Ives (1955) equation. This is discussed in the section empirical improvement of model and fitting. Pressure drop increased linearly with increasing airflow rate as shown in the figures. As expected, the slope of pressure drop curves is observed to decrease as moisture content is reduced for a given bulk depth. Similar trends have been reported by Rabe and Currence (1975) for alfalfa leaves. The difference in the slope of the curves is only marginal at MC ≤ 52.9% w.b. and MC ≤ 52.2% w.b. for the leaves and chopped aerial vines, respectively, except in the bulk depth of 0.30 m (fig. 4). In general, the pressure drop for sweet potato leaves was lower compared to chopped sweet potato aerial vines, except at moisture content levels of 88.7% and 74.7% and bulk depth of 0.75 m for sweet potato leaves. One possible cause for the trend observed in 0.75 m bulk depth (fig. 3) is compaction due to the loading of the leaves in the airflow resistance measuring system. Generally, loading of the leaves in the chamber of the airflow resistance measuring system was a task that cannot be performed with greater consistency. However, Swetnam et al. (1990) stated that such inconsistency during loading should reflect what would occur in the field and is therefore an essential design consideration.

For comparison purposes, sweet potato leaves and chopped sweet potato aerial vines in the moisture content range of 88.7% to 11.0% w.b. and 88.1% to 12.2% w.b., respectively, and bulk depth of 0.75 m were compared with Reed et al. (2001) data for marigold flowers (fig. 5). The marigold flowers moisture conditions and bulk depth ranged from 84.8% to 10.3% and 0.15 to 1.0 m, respectively. Note the near linear relationship on a typical

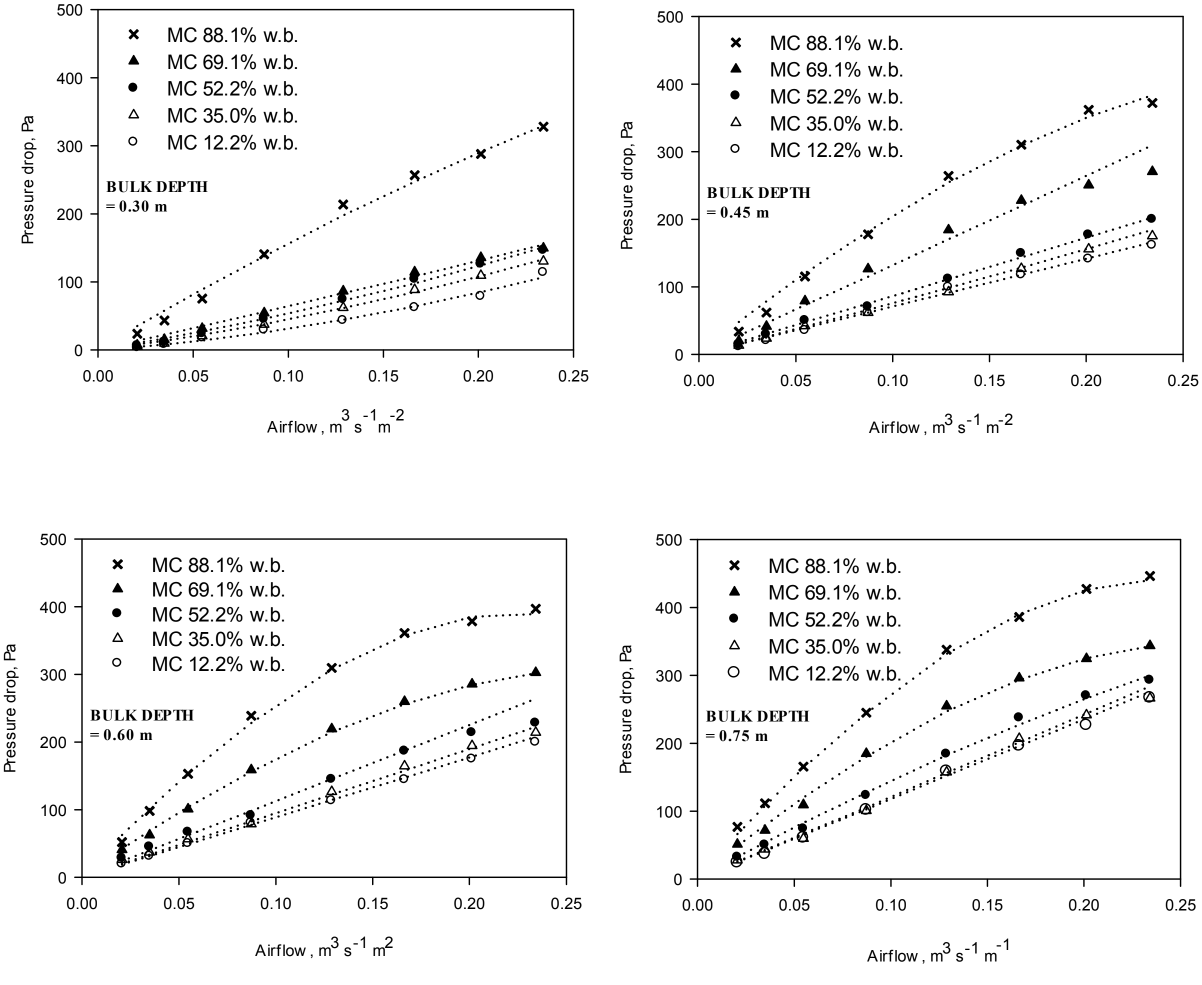

Figure 4. Relationship between pressure drop and airflow for chopped sweet potato aerial vines at different moisture contents and bulk depths.

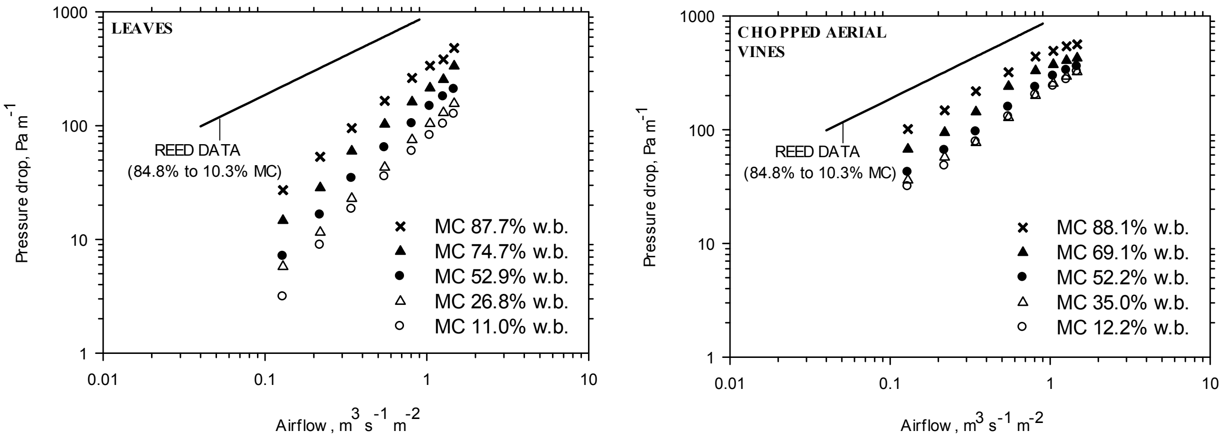

Figure 5. Pressure drop per unit bulk depth of sweet potato leaves and chopped sweet potato aerial vines at various moisture contents.

log-log plots of pressure drop per unit depth versus airflow rate for sweet potato leaves and chopped aerial vines. The pressure drop as a function of airflow for both sweet potato leaves and chopped sweet potato aerial vines was found below the values for marigold flowers. A closer look at figure 5 indicates a steep slope for sweet potato leaves when compared with the cited data. The curves for chopped sweet potato aerial vines are almost parallel, indicating a fairly constant slope in comparison with marigold flowers.

Table 2 summarizes the analysis of variance of the effects of airflow rate, moisture content, and bulk depth on pressure drop for both sweet potato leaves and chopped sweet potato aerial vines. All three variables and their interactions significantly ($P < 0.01$) affected pressure drop, but airflow had the most significant effect on pressure drop for both sweet potato leaves and chopped sweet potato aerial vines followed by moisture content and bulk depth.

Bulk density, which varied from 29.57 to 112.63 kg m^{-3} for sweet potato leaves and from 83.99 to 317.23 kg m^{-3} for chopped sweet potato aerial vines, was found to increase with increasing bulk depth (fig. 6). In the case of sweet potato leaves, at moisture content of 88.7% to 11.0% w.b., the change in bulk density was less noticeable, as depicted by the lower slope of the regression lines. Conversely, at moisture content of 88.1% and 69.1% w.b. for chopped sweet potato aerial vines, the change in bulk density with bulk depth was more obvious, defined by the larger slope of the regressions lines. At moisture contents below 50% w.b. in all test cases, the slope was the lowest underscoring the reduced influence on bulk density. Interestingly, as the drying process progresses for a given bulk depth of sweet

Table 2. Results of statistical analysis showing the effects of airflow rate (V), bulk depth (L), and moisture content (MC) on pressure drop for sweet potato leaves and chopped sweet potato aerial vines.

Sweet Potato Components	Variable	DF[a]	Sum of Squares	F-Value[b]
Leaves	V	7	943109.986	2544.681
	L	3	212821.926	1339.875
	MC	4	541730.399	2557.951
	V × L	21	94109.187	84.641
	V × MC	28	229354.103	154.710
	MC × L	12	61930.090	97.474
Chopped aerial vines	V	7	2972015.922	1830.284
	L	3	540996.788	777.390
	MC	4	1194636.034	1287.482
	V × L	21	89933.043	18.461
	V × MC	28	277367.451	42.703
	MC × L	12	29723.725	10.678

[a] Degrees of freedom.

[b] All variables and their interactions significantly affected the static pressure drop at P = 0.01.

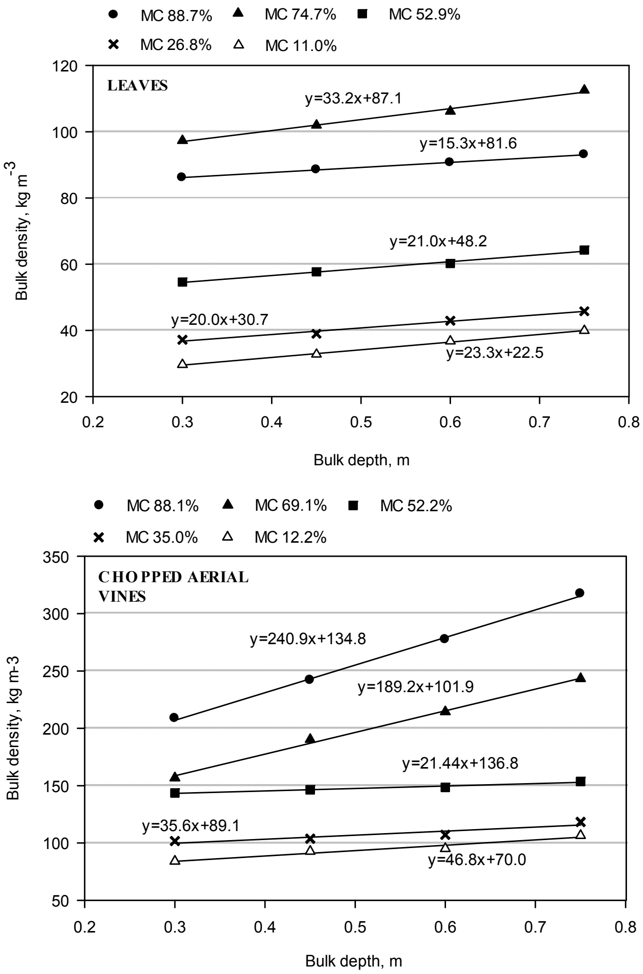

Figure 6. Bulk density vs. bulk depth at different moisture contents for sweet potato leaves and chopped sweet potato aerial vines. With three replicates at each data point, r^2 was at least 0.9943 for leaves and 0.8652 for chopped aerial vines in each of the five regression equations for the charts (leaves and chopped aerial vines).

potato leaves, their bulk density increases to a maximum value at 74.7% w.b. moisture content and suddenly starts to decline with further drying. The sweet potato leaves tend to mat from the beginning of the drying process (at 74.7% w.b), a phenomenon best ascribed to the large shrinkage that occurs as a result of significant changes in the leaf structure. Similar observation has being reported for air-dried leaves of *Mellisa officinalis* L. (Argyropoulos and Müller, 2014) and marigold flowers, var. I822 and EI236 (Reed et al., 2001). Bulk density of the chopped sweet potato aerial vines continue to drop up to the minimum moisture content (12.2% w.b.) as the products dry for a given initial bulk depth. In all experimental batches, bulk density continues to decline but at varying rates with further drying.

EMPIRICAL IMPROVEMENT OF MODEL AND FITTING

Initial model fitting based on equation 1(model fitting results not shown) shows that the Hukill and Ives (1955) equation can be used to accurately describe airflow resistance through sweet potato leaves and chopped sweet potato aerial vines. The coefficient of determination values was $r^2 \geq 98.8\%$ in all the test cases. Though the initial model fitting proved accurate, this only provides airflow resistance information in limited operation conditions. In practice, forced-air dryers are designed to be operated in more general conditions with products of different moisture conditions and bulk depth values. In order to apply the results of this work to broader applications, de-rating factors are inserted into the Hukill and Ives (1955) equation. Equations 2 and 3 are the empirical de-rating modification of equation 1 for sweet potato leaves and chopped sweet potato aerial vines, respectively.

$$\frac{\Delta P}{L} = \frac{aV^2}{Log_e\left(1+bV\right)}\left[1+c\left(MC-50.82\right)\right]\times\left[1+d\left(L-0.3\right)\right] \tag{2}$$

$$\frac{\Delta P}{L} = \frac{aV^2}{Log_e\left(1+bV\right)}\left[1+c\left(MC-51.34\right)\right]\times\left[1+d\left(L-0.3\right)\right] \tag{3}$$

where

MC = moisture content of sweet potato leaves or chopped sweet potato aerial vines (% w.b.),

c and d = empirical constants.

Equations 2 and 3 are based on the following observations. The moisture content for sweet potato leaves and chopped sweet potato aerial vine components ranged from 88.7% to 11.0% w.b. and 88.1% to 12.2% w.b., respectively. The average (50.82% w.b. for leaves and 51.34% w.b. for chopped aerial vines) was set as the base point. According to Yang et al. (2011), the de-rating factor will affect the final results if the average expected moisture content is much greater. In addition, 0.3 m was selected as the baseline bulk thickness to account for possible compactions, especially when designing forced-air dryers to be operated up to 1.5 m bulk depth as indicated by Müller and Heindl (2006) for medicinal plants. Based on the above considerations, all the resistance to airflow results were fitted into equations 2 and 3 for each data set of fixed moisture content and depth. The estimated parameters a, b, c, and d, along with statistical parameters,

Table 3. Estimated parameters and comparison criteria of equations 2 and 3 at various moisture content and bulk depth for sweet potato leaves and chopped sweet potato aerial vines.

Depth (m)		Moisture Content (% w.b)									
		88.7	74.7	52.9	26.8	11.0	88.1	69.1	52.2	35.0	12.2
		Leaves					Chopped Aerial Vines				
0.30	a	1963.437	3274.073	1139.061	635.784	1868.641	-2669.282	426.314	3505.199	757.708	3888.749
	b	14.484	37.241	29.839	9.922	400.394	-1.298	0.563	4.514	6.908	20.556
	c	0.021	0.019	0.384	-0.029	-0.015	-0.005	-0.010	-0.503	-0.128	0.003
	d	1.000	1.000	1.000	1.000	1.000	0.500	0.500	0.500	0.500	0.50
	r^2	0.996	0.995	0.999	0.998	0.993	0.991	0.991	0.995	0.997	0.988
	RMSE	2.65	2.84	0.50	0.71	1.05	10.49	4.94	3.74	2.51	3.92
	P (%)	4.68	6.97	7.17	5.68	5.66	7.18	5.95	5.64	5.62	7.11
0.45	a	125.088	2567.103	1953.094	2109.615	1071.184	-2700.049	-456.011	123.130	1092.673	1893.370
	b	0.002	4.889	14.426	19.602	16.307	-2.262	0.001	0.014	0.652	0.002
	c	-0.023	0.005	-0.163	-0.008	0.011	-0.073	-0.064	-1.077	0.022	0.025
	d	-5.868	-1.573	5.140	-1.918	8.582	-14.415	-6.525	2.220	-2.102	-6.434
	r^2	0.989	0.993	0.997	1.000	0.992	0.993	0.972	0.997	0.998	0.994
	RMSE	8.20	4.52	1.43	0.31	0.95	10.26	16.88	3.42	4.46	4.09
	P (%)	8.37	5.65	3.88	8.15	7.60	5.76	6.48	6.81	11.76	10.74
0.60	a	156.125	1319.359	2418.920	1649.670	1531.051	-3528.294	-6041.266	91.869	155.393	85.611
	b	0.001	1.146	7.513	9.319	11.586	-3.204	-2.724	0.001	0.001	0.001
	c	-0.024	-0.024	-0.235	-0.028	0.012	-0.073	-0.106	0.580	0.057	0.024
	d	-3.026	1.881	3.286	-0.847	2.955	-8.863	-6.828	-3.306	-3.036	-2.763
	r^2	0.979	0.992	0.996	0.998	0.997	0.996	0.999	0.983	0.994	0.999
	RMSE	17.67	5.87	2.70	1.30	1.47	8.10	3.39	14.16	5.29	3.56
	P (%)	8.62	5.72	5.59	5.58	8.48	4.40	1.89	10.94	4.47	10.00
0.75	a	1331.277	2009.868	1707.572	4021.799	3470.859	-4465.420	-3620.858	-3105.986	73.937	8.019
	b	1.217	5.839	6.813	11.668	13.289	-3.012	-2.788	-1.461	0.001	0.001
	c	0.020	0.018	0.495	0.022	0.014	-0.068	0.039	-1.992	0.055	0.044
	d	-0.167	2.135	0.558	3.164	3.734	-5.478	0.178	-4.522	-1.872	-2.688
	r^2	0.995	0.997	0.994	0.997	0.998	0.999	0.997	0.996	0.995	0.997
	RMSE	11.05	6.89	6.06	3.49	2.69	5.17	5.80	5.92	6.26	9.44
	P (%)	9.42	3.44	10.96	5.67	7.61	2.36	4.00	5.81	5.12	10.67

are summarized in table 3. The values of r^2 and RMSE obtained are ranging, respectively, from 97.9% to 100% and from 0.31 to 17.67 for the sweet potato leaves and from 97.2% to 99.9% and from 2.51 to 16.88 for chopped sweet potato aerial vines. The P-values were below 10% in 35 test cases with maximum $P \leq 11.76\%$. It is generally considered that (P) values below 10% indicate an adequate fit for practical purposes (Park et al., 2002). The statistical analysis of the improved Hukill and Ives (1955) equation indicates that it can be used to predict airflow resistance through sweet potato aerial vine components. Therefore, the 40 data set listed in table 3 can be used by designers for predicting the airflow resistance to overcome when designing forced-air drying systems for sweet potato aerial vine components. Once the airflow resistance has been determined, a requisite fan for forcing the air through bulk sweet potato aerial vine components can be selected.

CONCLUSION

The study provides information on the resistance to airflow through sweet potato leaves and chopped sweet potato aerial vines at various moisture contents and bulk depths. The resistance to airflow was significantly affected by all three variables (airflow, moisture content, and bulk depth) and their interaction, but airflow rate had the most significant effect on pressure drop of both sweet potato leaves and chopped sweet potato aerial vines. Comparing the data in this study with marigold flowers cited in literature, the curves of sweet potato leaves and chopped sweet potato aerial vines at the studied moisture content range were found below the values for marigold flowers. Bulk density is greatly affected by moisture content and ranged from 29.57 to 112.63 kg m^{-3} for sweet potato leaves and from 83.99 to 317.23 kg m^{-3} for chopped sweet potato aerial vines. Since moisture content and bulk depth were significant in determining airflow resistance, an empirical ‘‘de-rating’’ modification of Hukill and Ives (1955) equation was developed and used to predict pressure drop across the various samples investigated. The developed models provided a good fit to the experimental pressure drop data obtained in the range of airflows, moisture contents, and bulk depth under consideration.

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REFERENCES

Anderson, D. S., Abubakar, Y., Young, J. H., & Johnson, W. H. (1998). Pressure vs. airflow characteristics through fresh intact and cut-strip tobacco. *Trans. ASAE, 41*(6), 1747-1753. http://dx.doi.org/10.13031/2013.17318

Argyropoulos, D., & Muller, J. (2014). Effect of convective, vacuum and freeze drying on sorption behaviour and bioactive compounds of lemon balm (*Melissa officinalis* L.). *J. Appl. Res. Med. Aromat. Plants, 1*(2), 59-69. http://dx.doi.org/10.1016/j.jarmap.2014.06.001

ASABE Standards. (2011). D272.3: Resistance to airflow of grains, seeds, other agricultural products and perforated metal sheets. St. Joseph, MI: ASABE.

ASABE Standards. (2012). D358.3: Moisture measurements-Forages. St. Joseph, MI: ASABE.

Brown, D. L., & Chavalimu, E. (1985). Effects of ensiling or drying on five forage species in western Kenya: *Zea mays* (maize stover), *Pennisetum purpureum* (Pakistan napier grass), *Pennisetum sp.* (bana grass), *Impomea batata* (sweet potato vines) and *Cajanus cajan* (pigeon pea leaves). *Anim. Feed Sci. Technol., 13*(1), 1-6. http://dx.doi.org/10.1016/0377-8401(85)90037-9

Cooper, S. C., & Sumner, H. R. (1985). Airflow resistance of selected biomass materials. *Trans. ASAE, 28*(4), 1309-1312. http://dx.doi.org/10.13031/2013.32430

Ergun, S. (1952). Fluid flow through packed columns. *Chem. Eng. Prog., 48*, 89-94.

Farrell, D. J., Jibril, H., Perez-Maldonado, R. A., & Mannion, P. F. (2000). A note on a comparison of the feeding value of sweet potato vines and lucerne meal for broiler chickens. *Anim. Feed Sci. Technol., 85*(1), 145-150. http://dx.doi.org/10.1016/S0377-8401(00)00118-8

Grubecki, I. (2015). Airflow versus pressure drop for a mixture of bulk wood chips and bark at different moisture contents. *Biosyst. Eng., 139*, 100-110. http://dx.doi.org/10.1016/j.biosystemseng.2015.08.008

Gunasekaran, S., & Jackson, C. Y. (1988). Resistance to airflow of grain sorghum. *Trans. ASAE, 31*(4), 1237-1240. http://dx.doi.org/10.13031/2013.30850

Hukill, W. V., & Ives, N. C. (1955). Radial airflow resistance of grain. *Agric. Eng., 36*(5), 332-335.

Iqbal, T., Eckhoff, S. R., Syed, A. F., Nizami, A.-S., & Sadef, Y. (2015). Airflow resistance of chopped miscanthus on drying platform. *Trans. ASABE, 58*(2), 487-492. http://dx.doi.org/10.13031/trans.58.10827

Irvine, D. A., Jayas, D. S., & Mazza, G. (1993). Resistance to airflow through clean and soiled potatoes. *Trans. ASAE, 36*(5), 1405-1410. http://dx.doi.org/10.13031/2013.28478

Ishida, H., Suzuno, H., Sugiyama, N., Innami, S., Tadokoro, T., & Maekawa, A. (2000). Nutritive evaluation on chemical components of leaves, stalks and stems of sweet potatoes (*Ipomoea batatas poir*). *Food Chem., 68*(3), 359-367. http://dx.doi.org/10.1016/S0308-8146(99)00206-X

Janjai, S., & Tung, P. (2005). Performance of a solar dryer using hot air from roof-integrated solar collectors for drying herbs and spices. *Renewable Energy, 30*(14), 2085-2095. http://dx.doi.org/10.1016/j.renene.2005.02.006

Jones, D., & Von Bargen, K. L. (1992). Some physical properties of milkweed pods. *Trans. ASAE, 35*(1), 243-246. http://dx.doi.org/10.13031/2013.28594

Kristensen, E. F., & Kofman, P. D. (2000). Pressure resistance to air flow during ventilation of different types of wood fuel chip. *Biomass Bioenergy, 18*(3), 175-180. http://dx.doi.org/10.1016/S0961-9534(99)00089-6

Li, W., & Sokhansanj, S. (1994). Generalized equation for airflow resistance of bulk grains with variable density, moisture content and fines. *Drying Technol., 12*(3), 649-667. http://dx.doi.org/10.1080/07373939408959982

Müller, J., & Heindl, A. (2006). Drying of medicinal plants. In R. J. Bogers, L. E. Craker, & D. Lange (Eds.), *Medicinal and aromatic plants-agricultural, commercial, ecological, legal, pharnmacological and social aspects* (Vol. 17, pp. 237-258). Berlin, Germany: Wageningen UR Frontis Series.

Park, K. J., Vohnikova, Z., & Brod, F. P. R. (2002). Evaluation of drying parameters and desorption isotherms of garden mint leaves (*Mentha crispa* L.). *J. Food Eng., 51*(3), 193-199. http://dx.doi.org/10.1016/S0260-8774(01)00055-3

Rabe, D. L., & Currence, H. D. (1975). Air flow resistance and density of alfalfa leaves. *Trans. ASAE, 18*(5), 932-934. http://dx.doi.org/10.13031/2013.36710

Reed, S. D., Armstrong, P. R., Brusewitz, G. H., & Stone, M. L. (2001). Resistance of marigold flowers to airflow. *Trans. ASAE, 44*(3), 639-642. http://dx.doi.org/10.13031/2013.6091

Román, F., & Hensel, O. (2014). Real-time product moisture content monitoring in batch dryer using psychrometric and airflow measurements. *Comput. Electron. Agric., 107*, 97-103. http://dx.doi.org/10.1016/j.compag.2014.05.017

Sadaka, S., Magura, C. R., & Mann, D. D. (2002). Vertical and horizontal airflow characteristics of wood/compost mixtures. *Appl. Eng. Agric., 18*(6), 735-741. http://dx.doi.org/10.13031/2013.11321

Shedd, C. K. (1953). Resistance of grains and seeds to air flow. *Agric. Eng., 34*(9), 616-619.

Suggs, C. W., & Lanier, A. (1985). Resistance of wood chips and sawdust to airflow. *Trans. ASAE, 28*(1), 293-295. http://dx.doi.org/10.13031/2013.32244

Suggs, C. W., Zimmer, A. L., & Gore, J. W. (1985). Pressure vs. air flow through fresh tobacco leaves. *Trans. ASAE, 28*(5), 1664-1667. http://dx.doi.org/10.13031/2013.32495

Sugiura, R., & Watanabe, T. (2011). Effect of airflow drying and steam blanching on polyphenol retention in sweet potato leaves. *Trans. ASABE, 54*(2), 563-569. http://dx.doi.org/10.13031/2013.36460

Swetnam, L. D., Casada, M. E., & Walton, L. R. (1990). Airflow through densely packed burley tobacco leaves. *Appl. Eng. Agric., 6*(3), 334-336. http://dx.doi.org/10.13031/2013.26392

Tabil, L. G., Kienholz, J., Hong, Q. P., & Eliason, M. V. (2003). Airflow resistance of sugarbeet. *J. Sugar Beet Res., 40*(3), 68-86. http://dx.doi.org/10.5274/jsbr.40.3.67

Teguia, A., Njwe, R. M., & Nguekouo Foyette, C. (1997). Effects of replacement of maize with dried leaves of sweet potato (*Hypomoea batatas*) and perennial peanuts (*Arachis glabrata* Benth) on the growth performance of finishing broilers. *Anim. Feed Sci. Technol., 66*(1), 283-287. http://dx.doi.org/10.1016/S0377-8401(96)01110-8

VDI/VDE. (1983). Netzmessungen in strömungsquerschnitten (Blatt 3): Bestimmung des Gasstromes in Leitungen mit Kreis-, Kreisring- oder Rechteckquerschnitt. Düsseldorf, Germany: VDI-Verlag.

Woolfe, J. A. (1992). *Sweet potato: An untapped food resource.* Cambridge, U. K.: Cambridge University Press.

Yang, L., Wang, X., Funk, T. L., & Gates, R.S. (2011). Biofilter media characterization and airflow resistance test. *Trans. ASABE, 54*(3), 1127-1136. http://dx.doi.org/10.13031/2013.37104