Potential Water Retention Capacity as a Factor in Silage Effluent Control: Experiments with High Moisture By-product Feedstuffs

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ABSTRACT : The role of moisture absorptive capacity of pre-silage material and its relationship with silage effluent in high moisture by-product feedstuffs (HMBF) is assessed. The term water retention capacity which is sometimes used in explaining the rate of effluent control in ensilage may be inadequate, since it accounts exclusively for the capacity of an absorbent incorporated into a pre-silage material prior to ensiling, without consideration to how much the pre-silage material can release. A new terminology, 'potential water retention capacity' (PWRC), which attempts to address this shortcoming, is proposed. Data were pooled from a series of experiments conducted separately over a period of five years using laboratory silos with four categories of agro by-products (n = 27) with differing moisture contents (highest 96.9%, lowest 78.1% in fresh matter, respectively), and their silages (n = 81). These were from a vegetable source (Daikon, *Raphanus sativus*), a root tuber source (potato pulp), a fruit source (apple pomace) and a cereal source (brewer's grain), respectively. The pre-silage materials were adjusted with dry in-silo absorbents consisting wheat straw, wheat or rice bran, beet pulp and bean stalks. The pooled mean for the moisture contents of all pre-silage materials was 78.3% (±10.3). Silage effluent decreased (p<0.01), with increase in PWRC of pre-silage material. The theoretical moisture content and PWRC of pre-silage material necessary to stem effluent flow completely in HMBF silage was 69.1% and 82.9 g/100 g in fresh matter, respectively. The high correlation (r = 0.76) between PWRC of ensiled material and silage effluent indicated that the latter is an important factor in silage-effluent relationship. (**Key Words :** Absorbent, Effluent, High Moisture By-product Feedstuff, Potential Water Retention Capacity, Pre-silage Material)

INTRODUCTION

Ensiling of high moisture materials meant for ruminant livestock feeding involves difficulties not only in minimizing losses of silage nutrients but also in drainage through effluent, with the attendant environmental consequences. Silage effluent is considered one of the most common agricultural pollutants of water courses (Spillane and O'Shea, 1973; Woolford, 1978). Most direct ensiled grasses and whole crop materials are unable to retain their moisture when ensiled, and consequently the use of wilting prior to ensiling has been widespread. The process of silage effluent control as well as nutrients retention is of critical importance from an environmental perspective and several methods have been suggested to address this problem,

especially during the ensiling of low dry matter materials without compromising silage quality. Prominent among them is the incorporation of dry absorbents to materials prior to ensiling (Done and Appleton, 1989; Ferris and Mayne, 1994; Okine et al., 2007), or the use of proprietary absorbents (O'Keily, 1991; Moore and Kennedy, 1994).

The most obvious determinant of silage effluent flow is the moisture content of the pre-silage material (Castle and Watson, 1973; Woolford, 1978). However, this may be influenced by the chemical or physical conditions of the ensiled material within the silo (Woolford, 1978), added microbial inoculant (Zhung and Kumar, 2000) or nature of fiber of the material, since fibrous materials hold water differently (Robertson and Eastwood, 1981a).

Water retention capacity (WRC), which is used interchangeably with 'water holding capacity', is often used to describe hydration properties of fiber (Robertson and Eastwood, 1981b; Auffret et al., 1994; Robertson et al., 2000). In silage terminology, it represents the amount of moisture in grams that a dry absorbent can hold or retain per its dry matter weight when incorporated with a pre-

silage material, and is used to describe the absorptive capacity of dry materials in silage effluent control (Jones and Jones, 1996). The use of this measurement in silage terminology, however, is inadequate, since it accounts for the amount of moisture that the absorbent (often dry) material can 'hold' or 'absorb' without reference to the moisture content of the pre-silage material or how much moisture the pre-silage material can 'release' or 'retain' or is available for absorption.

Relationships between the dry matter content of pre-silage material and effluent production have been established (Jones and Murdoch, 1954; Sutter, 1957; Castle and Watson, 1973), yet, despite the importance in silage effluent studies, there is no mention in the literature of the relationship between the water retention capacity of pre-silage materials ensiled either alone, or with absorbents, and the subsequent effluent emanating from the silages. Knowledge of this is vital in predicting the threshold at which zero effluent from silages is possible on the basis of the absorptive and/or retention capacity of the material prior to ensilage and may be important in silage effluent control strategies.

In a previous study we (Okine et al., 2007) implied the existence of a relationship between WRC and moisture content of high moisture by-product feedstuff (HMBF) material vis-à-vis silage effluent. The present study investigates this relationship with data gathered from a series of experiments using HMBF materials. A novel terminology, potential water retention capacity (PWRC), which seeks to relate between pre-silage materials (ensiled either alone or with an absorbent) and effluent production is proposed. The relationship between moisture, PWRC and fiber (NDF) of pre-silage material and effluent from the resultant silage as well as the optimal PWRC necessary to completely stem effluent flow in HMBF is discussed.

MATERIALS AND METHODS

Data were pooled from a series of experiments conducted separately over a period of five years using laboratory silos. These involved the ensiling of HMBF (n = 27) without or with absorbents and are divided into 5 groups (Table 1); each group consisting of the pre-silage material and moisture adjusted treatments using various absorbents as follows:

Group 1 (Potato pulp A) : This included four treatments consisting of pre-silage material without moisture adjustment (control, PP1) and material adjusted with wheat bran (absorbent) to three different moisture levels (PP2, PP3 and PP4).

Group 2 (Potato pulp B) : This included 7 treatments consisting of potato pulp adjusted without or with three

different absorbents as follows:

Control, without moisture adjustment (PPC); adjusted with wheat bran to two moisture levels (PPWB 1 and PPWB 2); adjusted with dried beet pulp to two moisture levels (PPBP 1 and PPBP 2); and adjusted with wheat straw to two moisture levels (PPWS 1 and PPWS 2).

Group 3 (BG) : Brewer's grain consisting of three treatments adjusted without absorbent (C), with dried beet pulp (BP), or wheat bran (BW).

Group 4 : Apple pomace consisting of four treatments adjusted without absorbent (AP), with dried beet pulp (ABP), rice bran (ARB), or wheat bran (AWB).

Group 5 : Daikon (Oriental radish, *Raphanus sativus*) by-product without absorbents segregated according to size of chopping of the by-product prior to ensiling; DKS, DKM, DKL, and DN; with wheat straw absorbents (DA and DWS); with dried bean stalks/hulls (DBH); with dried beet pulp (DBP), and with wheat bran (DWB).

All groups were ensiled at ambient temperatures of between 18-25°C using pipe and bucket silos made from poly vinyl chloride (PVC) equipped with a drain tap enabling effluent flow and measurement. These methods are fully described in a previous paper (Okine et al., 2007). Data of chemical components of pre-silage materials including moisture, WRC, PWRC, NDF, and silage characteristics (pH, lactic acid content and effluent output of the silages) were the parameters considered. Other chemical parameters such as sugar content, buffering capacity, microbial numbers or physical parameters such as pressure and density were excluded because of limitations of available data.

Chemical analyses

Moisture, pH, lactic acid and NDF were analyzed using standard procedures as described in a previous paper (Okine et al., 2005). Water retention capacity (WRC) was adapted from the method of Robertson et al. (2000) but modified for the sake of procedural convenience as follows: one gram of air-dry weight of each HMBF material (dried at 60°C for 48 h and milled to <1 mm) was measured into a 50 ml centrifuge tube and hydrated with 30 ml distilled water containing 0.02 g sodium azide per 100 ml as a bacteriostat. The tube containing the sample was then equilibrated for 18 h at room temperature and its contents were transferred to a glass filter with a pore size of 100-160 μm, (1G P160, Sibata Company, Tokyo, Japan) and drained under a pressure of 2 g/cm² with a pressure pump (Compact air pump, NUP-1, AS-ONE Company, Tokyo, Japan) for 2 min. The glass filter containing the sample was weighed, oven-dried at 135°C for two hours and weighed again. The WRC of the material was calculated as the amount of water retained by the pellet (g moisture/g dry weight) after

Table 1. Chemical parameters of some high moisture by-product feedstuffs (HMBF) adjusted with or without absorbents and effluent outputs from their silages*

Grouping	HMBF	Moisture (% FM)	WRC (g/g DM)	PWRC (g/100 g FM)	NDF (% DM)	Effluent (g/100 g FM)
Group 1 (Potato pulp A)[1]	PP1	88.1	2.98	35.5	32.8	11.3[a]
	PP2	79.4	2.44	50.2	35.3	8.9[ab]
	PP3	74.3	2.22	57.1	36.6	6.8[b]
	PP4	64.3	2.00	71.4	40.8	0.2[c]
Group 2 (Potato pulp B)[2]	PPC	78.1	2.43	53.1	32.6	0.7[a]
	PPWB 1	74.1	2.37	61.3	33.5	0.4[a]
	PPWB 2	68.4	2.25	71.0	39.3	0.0[b]
	PPBP 1	73.1	2.44	65.7	35.1	0.0[b]
	PPBP 2	68.0	2.45	78.3	37.5	0.0[b]
	PPWS 1	70.0	2.16	64.7	54.0	0.0[b]
	PPWS 2	64.9	2.17	76.3	58.0	0.0[b]
Group 3 (Brewer's grain BG)[3]	C	81.4	3.11	57.6	38.3	18.4[a]
	BP	66.3	2.66	89.4	40.5	0.0[c]
	WB	64.0	2.00	71.9	42.1	4.9[b]
Group 4 (Apple pomace P)[4]	AP	91.9	6.27	50.9	46.6	39.1[a]
	ABP	82.1	5.08	90.7	50.8	3.7[c]
	ARB	70.8	2.60	76.0	35.6	7.3[b]
	AWB	73.4	3.31	88.2	48.9	9.3[b]
Group 5 (Daikon D)[5]	DKM	96.9	7.02	21.5	21.1	53.9[a]
	DKS	96.8	7.02	22.5	21.1	54.5[a]
	DKL	96.6	7.03	23.6	21.1	49.6[a]
	DN	93.4	2.40	15.8	21.1	37.8[b]
	DA	83.7	3.52	57.4	69.0	3.2[e]
	DWS	81.6	4.08	75.1	72.5	0.0[e]
	DBH	79.5	3.95	80.9	59.5	10.3[c]
	DBP	79.3	4.25	87.9	41.5	15.2[c]
	DWB	73.6	2.49	65.6	50.7	20.1[d]
Statistical parameter						
Mean	-	78.3	3.43	61.5	41.3	-
Standard deviation	-	10.3	1.6	21.8	13.6	-

* Effluent values are means of three samples; means with uncommon letters within a column for each effluent group differ significantly (p<0.05); HMBF = High moisture by-product feedstuff; WRC = Water retention capacity; PWRC = Potential WRC; NDF = Neutral detergent fiber; FM = Fresh matter; DM = Dry matter; g, gram.

[1] PP1, potato pulp control (A); PP2, PP3, PP4, (A) adjusted to various moisture levels with wheat bran.

[2] PPC, potato pulp control (B); PPWB1, PPWB2, (A) adjusted with wheat bran; PPBP1, PPBP, (B) adjusted with dried beet pulp; PPWS1, PPWS2, adjusted with wheat straw to different moistures, respectively.

[3] C = Brewer's grain control (BG); BP, WB, (BG) adjusted with dried beet pulp and wheat bran, respectively.

[4] AP = Apple pomace control (P); AP, ABP, ARB, AWB, (P) adjusted with dried beet pulp, rice bran and wheat bran, respectively.

[5] DKM, DKS, DKL, DN, daikon by-product without moisture adjustment (D); DA and DWS, DBH, DBP, DWB, (D) adjusted to moisture levels with wheat straw, bean stalks, dried beet pulp and wheat bran, respectively.

transfer to the glass filter. PWRC was defined as 'the amount of moisture in grams that a HMBF or a silage material can retain per 100 grams of the fresh matter weight'.

Statistical analysis

All data including those of pre-ensiling characteristics i.e. moisture, water retention capacity (WRC) and neutral detergent fiber (NDF) of the HMBF were analyzed using the statistical analyses software Excelstats for Windows 2004 (Microsoft Corporation, USA). Means from the silage effluent data were calculated from each group and analyzed separately and significant mean differences in effects were separated using the least significant different test and P values less than 0.05 considered statistically significant. Regressions were performed to study the relationships between the studied parameters and a multi-linear equation describing the relationship between effluent (dependent

variable) and moisture, PWRC and NDF (independent variables) was calculated using the software.

RESULTS

Moisture content of pre-silage HMBF material

The chemical parameters of the HMBF materials and silage effluent outputs are presented in Table 1. Each group consisted of the pre-silage material (control) followed by adjustments with in-silo absorbents into different moisture levels. In Groups 1 and 2, the moisture content of potato pulp was adjusted from 88.1-64.3 and 78.1-64.8% in fresh matter, respectively. In the brewer's grain and apple pomace experiments (Groups 3 and 4), adjustments reduced the moisture contents from 81.5-64.0 and 91.9-73.4% in fresh matter, respectively.

In the daikon by-product study (Group 5), data were pooled from three separate experiments involving the use of the by-product without/with adjustment with various absorbents. These reduced the high moisture of the material from 96.9-73.6% in fresh matter.

The pooled mean for moisture content in all the experiments was 78.3%.

Water retention capacity (WRC) and potential WRC

The WRC varied with type of HMBF, absorbent used and moisture content of the pre-silage material alone or the mixture, with a pooled mean of 3.43 g/g. However, a pattern was observed in reductions of WRC with increment in moisture contents of Groups 1, 2, 3 and 4. In Group 5, the opposite was true. The WRC values of the adjusted moistures (DA, DBP, DWS, DBH and DWB) were higher than that of DN, the source material. There was however, clear consistency in the pattern of PWRC, increasing with decrease in moisture content.

Fiber content

The fiber contents (NDF) were low in the pre-silage materials (control) but increased according to the fiber content of the absorbent introduced. Consequently,

Table 2. Mean fermentation characteristics of the HMBF silages used in the study

	Moisture range (%)	pH	Lactic acid (% DM)
Potato pulp A	89-67	3.75±0.14	5.59±1.48
Potato pulp B	80-67	3.39±0.15	2.17±0.62
Brewer's grain	84-67	3.60±0.12	1.44±0.16
Apple pomace	89-70	3.49±0.05	7.97±2.48
Daikon by-product	94-75	3.80±0.18	4.73±3.10

Values are means±standard deviation.
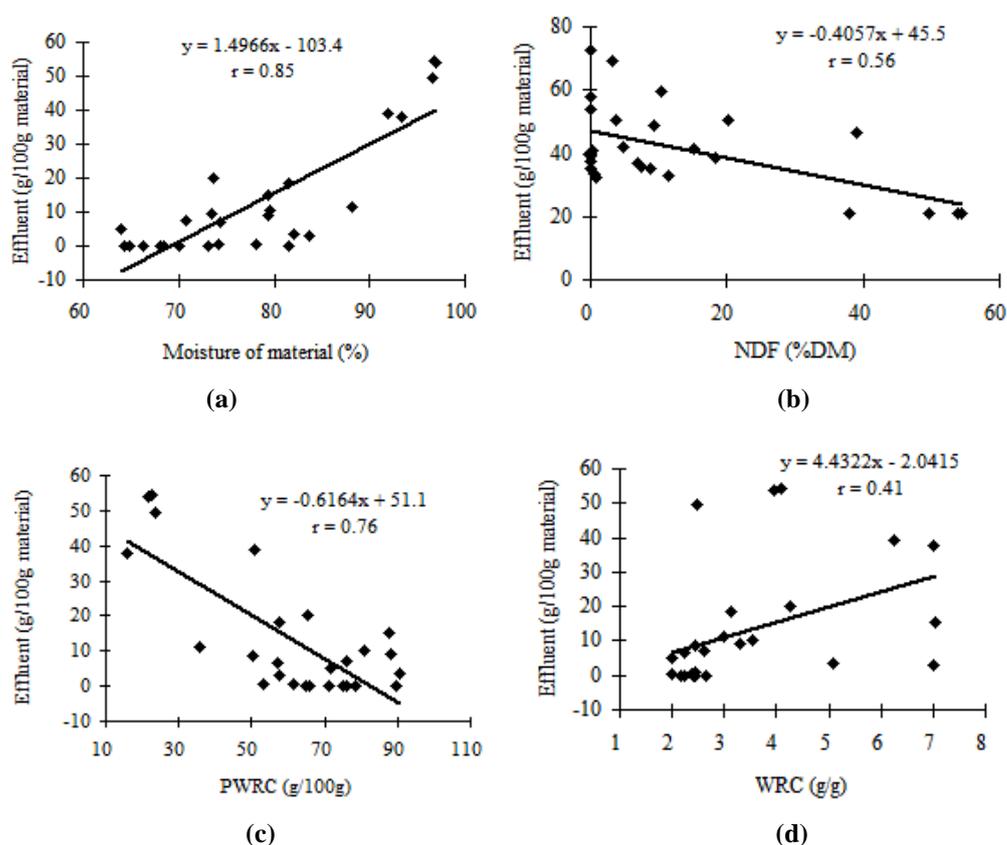HMBF = High moisture by-product feedstuff.

absorbents high in fiber, such as wheat straw and bean stalks, tended to increase the NDF of daikon by-product (DA, DWS and DBH).

Silage effluent and relationship with pre-silage material

The silages underwent acceptable fermentation processes, as indicated by the average pH and lactic acid contents (Table 2). Effluent outputs varied with type, moisture and PWRC of the material. Differences in effluent outputs were obvious (p<0.05) with increase (p<0.05) in moisture content or addition of absorbent within each group. Daikon by-product silages produced the most effluent relative to the other HMBF silages.

Relationships were observed between the pre-silage characteristics of the HMBF and effluent produced from the silages (Figure 1). There was a positive relationship between effluent and moisture but inverse relationships with PWRC and NDF of the HMBF materials studied. A multi-regression equation was established as given below:

$$Y = 1.569M-0.1059PWRC-0.2159NDF-62.3$$
$$(R^2 = 0.71, n = 81, p<0.01)$$

where Y, effluent (g/100 g fresh matter of material); M, moisture content of the pre-silage material (%); PWRC, (potential water retention capacity of pre-silage material, in g/100 g FM); NDF, neutral detergent fiber of pre-silage material (% DM).

Based on regression equations from Figure 1(a, b), the theoretical moisture content and PWRC at which no effluent would be produced from the experiments were 69.1% in DM and 82.9 g/100 g in FM, respectively.

DISCUSSION

The pre-silage materials used in the experiments were typical of HMBF as indicated by the mean moisture value (78.3% in FM). Adjustments, especially of pre-silage materials such as daikon by-product and apple pomace with dry absorbents prior to ensiling, were necessary to enhance storage and more importantly, forestall excessive losses from their silages through effluent. The mean fermentation characteristics of the five groups of silages (Table 2) indicated an acceptable fermentation process in pH and lactic acid values, with the exception of brewer's grain silages, which had low lactic acid contents typical of silages made from the by-product (Nishino et al., 2001) in Japan. This is generally attributed to the low contents of sugar and high buffering capacity in brewer's grain, factors that are important for a successful silage fermentation process.

The WRC values as determined by the modified method (Table 3) were generally low compared with other reports

Figure 1. Relationships between moisture (a), NDF (b), PWRC (c), and WRC (d) of some HMBF (n = 27) and effluent output from their silages (n = 81).

for vegetable and fruit by-products in general (Thibault et al., 1992; Cho et al., 1997) but comparable to those of Auffret et al. (1994) for wheat bran and pea hulls (bean stalks and hulls), and (Dexter, 1961; Hillman and Thomas, 1974) for dried beet pulp, but only reflect the source of fiber and the method used. Water retention in fiber has been determined using different methods such as centrifugation, filtration, or suction pressure (McConnell et al., 1974; Robertson and Eastwood, 1981c; Chen et al., 1984), with

Table 3. Water retention capacity (WRC) of some HMBF materials and dry absorbents[1]

	WRC (g/g DM)
HMBF	
Daikon (root)	3.58±1.31
Apple pomace	3.12±0.54
Potato pulp	3.55±0.75
Dry absorbents	
Dried beet pulp	2.96±0.58
Wheat straw	3.08±0.40
Bean stalks and husks	2.58±0.52
Wheat bran	1.32±0.62

[1] Values are means of nine samples±standard deviation.
HMBF = High moisture by-product feedstuff.

each method measuring the amount of water associated with a sample under the defined conditions. This measurement, when used to explain the relationship between silage material and effluent output in ensilage, is however, inadequate. First, it accounts for the amount of moisture held or absorbed by the dry absorbent only, without reference to the fate of moisture of the pre-silage material. This omission can give misleading predictions of effluent outputs from the silages since fibrous materials of both material and absorbent used have differing absorption and retention capacities which, to a large extent, depend on the chemical activity of the water, pore size distribution of the fiber matrix and trapped water within the cell wall lumen (Robertson and Eastwood, 1981a). Secondly, the ability to retain effluent under the influence of chemical or physical conditions within the silo could be more relevant than the ability of the absorbent material *per se*. The use of microbial additives prior to ensiling (Ferris and Mayne, 1994; Okine, 2007; Okine et al., 2007) and/or the application of external forces, such as surface pressure (Dexter, 1961; Woolford, 1978) on the silo as pertains during ensilage, affect silages effluent outputs.

The definition of WRC in silage terminology as indicated by Jones and Jones, 1996 in our opinion entails

two moisture phases; (M1 and M2) expressed on DM basis in the equation below:

$$\frac{(M1+M2)}{DM} \qquad (1)$$

where $M1$, moisture content of absorbing material; $M2$, absorbed moisture.

A third component representing a pre-silage material when expressed on the basis of DM of the material (with or without an absorbent) per 100 g fresh matter, the equation becomes:

$$\frac{(M1+M2)}{DM} \times \frac{DM}{FM} = WRC \times DM \text{ (of the mixture)} \qquad (2)$$

Equation (2) is termed the 'potential water retention capacity (PWRC)', i.e., the WRC multiplied by the dry matter content (% of fresh matter) of the pre-silage material. In other words, 'the amount of water in grams that can be held per 100 grams of the pre-silage material when ensiled either alone or in combination with a dry in-silo absorbent'.

The PWRC of a pre-silage material takes into account both the 'moisture' element of the pre-silage material and the 'absorptive capacity' of the dry in-silo absorbent and this provides a more realistic approach in determining the retentive capacity of the mixture *vis-à-vis* silage effluent output. This is particularly valid during the addition of absorbents prior to ensilage and gives a reliable prediction of effluent outputs from materials particularly high in moisture such as HMBF. The lower the PWRC of a silage material, the more effluent is expected from its silage, and vice-versa, as shown in Table 1. This is true for the ensilage of HMBF, since effluent output is intrinsically a function of its PWRC, as indicated in (Figure 2) using different HMBF. It is evident that after ensiling, the PWRC of HMBF

reduces as effluent is released. The strong relationship between pre-silage material and silage PWRC (r = 0.92, p<0.01) validates this theory. The data in Figure 1(c, d) of the HMBF silage experiments showed a stronger effluent relationship with PWRC than with WRC (r = 0.76 vs. 0.41), an indication that the former may be more reliable than the latter as an index for effluent retention in HMBF silages. The regression equation between PWRC of the HMBF (n = 27) and effluent outputs (n = 81) from the silages (Figure 1c) is given below:

$$Y = -0.6164x-51.1 \qquad (r = 0.76, p<0.01)$$

where Y, effluent (g/100 g FM of ensiled material) and x, PWRC (g/100 g FM of pre-silage material).

From the given equation, the theoretical PWRC of a pre-silage material at which effluent production from its silage would be zero is 82.9 g/100 g FM. To achieve this, a combination of factors such as the moisture content and WRC of both pre-silage material and the absorbent need to be considered. The use of absorbents high in WRC and low moisture materials favor an elevated PWRC of the mixture.

The fiber content of both material and absorbent also plays an important role in both WRC and PWRC of pre-silage materials in relation to effluent retention in the silages. A typical illustration of this is given in Table 1. The WRC of the adjusted moistures DA, DBP, DWS, DBH and DWB were higher than that of DN, the source material, while the opposite was true for the other groups (PP1, PPC, C and AP). This could be attributed to the high NDF of the absorbents used which increased the low original NDF of DN (daikon by-product) nearly twofold. In the other groups, addition of absorbents, however, did not affect the NDF contents of the mixtures. The PWRC values, however, were consistent in increases, with increase in NDF contents. Both had inverse relationships with effluent output. Since fibrous
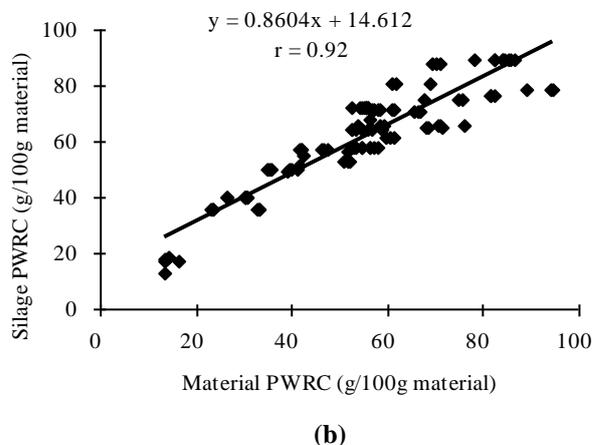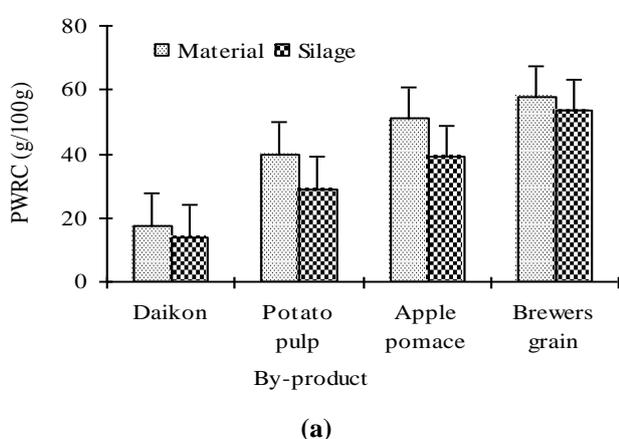

Figure 2. Potential water retention capacity of some HMBF materials and their silages with error bars (a), and regression equation showing the relationship between HMBF materials used in the study and their silages (b) (n = 81).

materials retain effluent better than non-fibrous materials (Jones and Jones, 1996), the PWRC and NDF relationships with effluent further validates the PWRC theory and introduces an important parameter in ensiling of wet materials.

The moisture content of a pre-silage material, based on the experiments, at which it is predicted that no effluent will be produced was 69.1% (or 30.9% DM). This figure is close to those of Bastiman (1976), Zimmer (1967) and Sutter (1957) for grasses and crops, who proposed dry matter content of pre-silage material at which no effluent would be produced to be between 29.9 and 30.7%. From the pooled mean values of the moisture contents of materials ensiled in this study, the results are particularly significant. It is therefore prudent that the moisture content during ensiling of HMBF does not go beyond 70%. The high correlation between effluent and PWRC validates the PWRC concept. The optimum PWRC level necessary to stem effluent completely in HMBF silages is 89.1 g/100 g FM and this introduces an important index in silage effluent studies.

CONCLUSION

It could be concluded that the terminology, potential water retention capacity (PWRC), is an important factor in the ensiling of high moisture by-product feedstuffs. The optimum PWRC of a pre-silage material necessary to stem effluent flow in high moisture by-product feedstuffs is 89.1 g/100 g FM and represents an important index in silage effluent studies. Further studies with a cross section of high moisture by-products feedstuff are warranted to validate this theory.

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