Chemical additives and the aerobic stability of silages

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1. Perspective

The most crucial step when ensiling any feedstuff is that it is stored in an air-free environment, thereby inhibiting the activity of the micro-organisms that cause aerobic deterioration. For as long as anaerobic conditions are maintained the aerobic activity of a wide range of micro-organisms is prevented. However, a harvested feedstuff will be exposed to air if silo filling and sealing are delayed, if the sealing of the silo is imperfect, or if the duration of exposure to air during feedout is too long. It will also be exposed to air when presented to livestock for consumption. In this latter case it may have been mixed with other dietary ingredients and be fully exposed to air. Since the first requirement when making and feeding silage is to manage all components of the process so as to minimise or prevent exposure to air, being successful in these tasks is the most cost-effective way to reduce the scale of aerobic losses that could occur. Silage additives, applied at ensiling or at feedout, should only be considered as a means to control aerobic losses once the relevant management practices for limiting aerobic deterioration have been undertaken correctly. Additives should not generally be relied upon to alleviate inadequate management.

There are circumstances where aerobic losses can be severe and where management practices cannot easily be altered to alleviate the problem. These are more likely when silage feedout and feeding occur during warm weather conditions and where the rate of use of silage is slower than optimal. Silages made from low buffering capacity feeds are often more susceptible.

Yeast are considered common initiators of aerobic deterioration, but bacteria can also be at fault, and both are usually succeeded in the deterioration process by moulds. Hence, the focus of chemical additives for limiting aerobic deterioration is to inhibit the aerobic activity of these micro-organisms while avoiding negative carryover effects to the rumen.

2. Organic chemical additives

2.1 Acids

Organic acid additives were originally used mainly to inhibit clostridial fermentations. This use has diminished as the general standard of silage-making has improved as well as due to issues relating to corrosion of metal, plastic and concrete and severe damage if they come into direct contact with animal tissue.

Formic acid. The main use of this additive has been to aid silage preservation, with the rate of application depending on the scale of the preservation challenge presented and the extent to which it was intended to restrict fermentation. Its use has been mainly with unwilted or lightly wilted herbages. When herbage ensiled without additive undergoes a clostridial fermentation then the even application of sufficient formic acid (2-4 l/t) helps prevent clostridial activity and stimulates a lactic acid fermentation instead. In contrast, when applied to herbage that would undergo a lactic acid dominant fermentation it restricts the extent of that fermentation thereby resulting in the silage having a higher concentration of unfermented water-soluble carbohydrates (WSC). Higher application rates (4-6 l/t) essentially prevent fermentation.

The data in Table 1 summarise a series of 78 laboratory silo experiments in which the conservation characteristics of ensiled unwilted grass silages were studied. In each experiment there were silages (4 silos/treatment) made without additive and with formic acid (850 g/kg) applied at 3 ml/kg (= 3 litres/tonne). The data have been segregated into those experiments where the herbages ensiled had 0-9 (n = 46 experiments), 10-19 (n = 17 experiments) and 20-30 (n = 15 experiments) g WSC/kg aqueous phase of the pre-ensiled herbage. In experiments where the herbage was in the lowest WSC category silage made without additive preserved very badly, and the standard of silage preservation improved as grass WSC category increased. There was a tendency for badly preserved silage to be more stable (smaller duration until pH or temperature rise commenced) when exposed to air than excellently preserved silage, and for it to have a smaller extent of aerobic deterioration (larger accumulated temperature rise during five days aerobiosis). This outcome is in accord with Ohyama *et al*. (1975). Formic acid significantly improved aerobic stability and reduced aerobic deterioration, having a larger effect where the extent of instability or deterioration was more severe (i.e. where silage made without additive was well preserved). This agrees with Crawshaw *et al.* (1980) who also showed that aerobic deterioration was progressively reduced as the rate of formic acid applied to grass was incrementally increased from 0 to 6 l/t. Similar benefits from formic acid have also been reported by Salawu *et al.* (2001), Adesogan and Salawu (2002) and Randby (2002), while Conaghan *et al.* (2009) has shown ammonium tetraformate (640 g formic acid + 70 g ammonia/kg; density 1.18 g/ml) also capable of enhancing aerobic stability.

Table 1. Silage fermentation and aerobic stability and deterioration characteristics - statistical summary of 78 laboratory silo experiments at Teagasc Grange comparing unwilted grass ensiled with no additive (NA) or with formic acid (FA)

Grass juice WSC g/kg		pH	NH_3-N g/kgN	Days to pH rise	Days to pH max.	Days to ^{O}C rise	Days to ^{O}C max.	Acc. ^{O}C rise to day 5[3]
20-30	NA	3.9	80	3.2	5.8	2.1	5.3	95
	FA	4.0	61	4.6	6.8	2.4	6.6	67
	s.e.	0.05	2.6	0.37	0.25	0.10	0.29	6.1
	P[1]	0.03	<0.001	0.002	0.002	0.007	<0.001	<0.001
	n[2]	15	15	15	13	15	11	15
10-19	NA	4.3	121	3.0	6.7	2.3	5.0	61
	FA	4.2	77	4.4	7.6	2.4	6.4	44
	s.e.	0.08	5.3	0.37	0.29	0.18	0.36	6.2
	P[1]	0.23	<0.001	0.002	0.013	0.71	0.002	0.015
	n[2]	17	17	15	11	15	11	17
0-9	NA	5.4	283	3.9	5.3	2.4	4.8	47
	FA	4.8	151	4.0	6.3	2.5	5.9	37
	s.e.	0.08	14.7	0.37	0.35	0.15	0.31	3.7
	P[1]	<0.001	<0.001	0.84	0.012	0.29	0.001	0.008
	n[2]	46	45	32	28	32	26	46

[1]2-tail probability; [2]number of experiments with pair of treatments compared; [3]Accumulated ^{O}C rise to day 5

Propionic acid. Although this additive has been widely used for preventing fungal growth on aerobically stored moist grain or hay it can also be applied to herbage at ensiling to help prevent yeast or mould activity at feedout. Its anti-fungal character derives from the undissociated molecule, and the anti-fungal effect increases as forage pH declines (Woolford, 1975a) reflecting its reduced state of dissociation. The anti-mycotic effect was further highlighted by Crawshaw *et al.* (1980) who found that propionic acid (990 g/kg) applied at progressively higher rates (from 0 to 10 l/t) restricted yeast and in particular mould growth, and reduced respiration (CO_2 production), during the exposure of silage to air. This effect reflected the progressively higher input of the active ingredient interacting with the correspondingly lower pH that ensued.

Propionic acid is rarely used as the sole agent in silage additives (at least partially due to its cost), and is more usually applied in a mixture with other acid ingredients. These acids are often applied as salts (in liquid or solid form) rather than as straight acids. Arbabi *et al.* (2008) compared four additives [(a) propionic acid, (b) propionic acid (0.85) + formic acid (0.15), (c) calcium propionate and (d) propionic acid (0.8) + formic acid (0.15) + ammonia (0.05); each additive applied at 0.1%; propionic acid in each additive was buffered] applied to forage maize at ensiling. Each additive gave a major improvement in silage aerobic stability, with the effects of propionic acid and to a slightly lesser extent propionic acid + formic acid giving the most consistent benefits.

Propionic acid or propionate based additives have been shown to improve aerobic stability or reduce aerobic deterioration when an adequate rate is applied (Ohyama *et al.*, 1975; Woolford and Cook, 1977; Kung *et al.*, 1998; Stacey *et al.*, 2001) but not when insufficient additive is used (Ohyama *et al.*, 1975; Kung and Ranjit, 2001; Kleinschmit *et al.*, 2005). The critical rate required will depend on the susceptibility of a particular silage to aerobic deterioration, as well as the ambient environment and management factors. It will also depend on the chemical nature of the propionate compound(s) used.

It has often been suggested in cases where “heating” is occurring in the exposed face of silage during feedout that spraying propionic acid on the face would stop the aerobic deterioration process. Besides the dangers (to whoever does the spraying) associated with such an application process, Pitt and Muck (1993) concluded that although the extent of deterioration and associated losses would decrease at the sprayed silage face, there would still be extensive deterioration in the silage beyond this treated surface layer because air would move freely through the treated zone. In fact, Ruxton and Gibson (1994) concluded that inhibiting deterioration at the exposed silage face leads to a deeper penetration of air into the silage with the result that no overall benefit accrues. Hence, spraying a silage face with propionic acid is not a recommended strategy for preventing aerobic losses during feedout. Any apparent benefit is therefore largely cosmetic. Similarly, spraying the surface of herbage in a silo immediately before sealing it beneath plastic film is unlikely to make a marked difference at feedout - Castor *et al.* (2006a; 2006b) sprayed wilted grass with buffered propionic acid (0.011 ml/cm^2) immediately before sealing it beneath plastic film and recorded no reduction in aerobic deterioration at feedout due to this treatment.

Propionic acid, or additives based on propionate, can be mixed with silage during the production of a total mixed ration (TMR). This was investigated by Kung *et al.* (1998) who reported that the adequate mixing of sufficient additive reduced yeast numbers and improved the aerobic stability of the TMR.

Other organic acids. Woolford (1995a; 1995b; 1998) screened the C_1 to C_{12} straight-chain fatty acids (formic, acetic, propionic, butyric, valeric, caproic, heptylic, caprylic, pelargonic, capric, hendecanoic and lauric, respectively), as well as lactic, acrylic and glycollic acids, for their anti-mycotic effects as silage additives. The longer straight-chain fatty acids from C_6 to C_{12} (but with the apparent exception of hendecanoic acid) were strongly antimycotic across a range of pH values. In contrast, acrylic, glycollic and lactic acids had a relatively modest impact on inhibiting yeast or mould activity.

Sorbic and benzoic acids are frequently used as food preservatives and have been considered as constituents of silage additives. Woolford (1975b) investigated the anti-mycotic effects of potassium sorbate and sodium benzoate. Both compounds were more effective at lower pH's and, although they were equally effective at pH 4, potassium sorbate was progressively more effective (on a molar basis) than sodium benzoate at pH 5 and 6. In practice, their effectiveness depends on the rate at which active ingredient is applied and the scale of aerobic stability challenge present. Thus, Kleinschmit *et al.* (2005) recorded major improvements in aerobic stability from potassium sorbate (plus EDTA; 0.1% addition rate of a 50:50 mixture) or sodium benzoate (0.1% addition rate).

Meanwhile, Pedroso *et al.* (2008) recorded a much larger benefit from sodium benzoate (1 g/kg) than potassium sorbate (0.3 g/kg) when added to sugarcane pre-ensiling. In contrast, Bernardes *et al.* (2003) recorded little benefit after applying sodium benzoate (at up to 3 g/kg) to marandu grass at ensiling.

More recently these additives have been co-applied with some lactic acid bacterial inoculants, partially to counteract the tendency of *Lactobacillus plantarum*-based additives to sometimes disimprove aerobic stability. Applying sodium benzoate (Saarisalo *et al.*, 2006; Pahlow *et al.*, 2004; O'Kiely *et al.*, 2008) or potassium sorbate (Pahlow *et al.*, 2004; Stryszewska and Pys, 2006) under such circumstances can improve aerobic stability or restrict the extent of aerobic deterioration at feedout. However, benefits to aerobic stability/deterioration from applying potassium sorbate or sodium benzoate are not guaranteed (O'Kiely *et al.*, 2006), with the critical application rate required presumably changing with the scale of aerobic deterioration challenge presented.

Additives such as sodium benzoate and potassium sorbate can also be mixed with silage at feedout. Saarisalo *et al.* (2006) applied a series of rates of these compounds (0, 15, 30 and 45 g/kg silage) to a range of silages and found that higher rates of application lead to a progressively larger curtailment of aerobic deterioration, and that the effects of potassium sorbate were more pronounced than those of sodium benzoate.

Caproic acid (added at 1.2 g/kg forage) applied to grass (Ohyama *et al.*, 1979) or maize (Ohyama and Hara, 1979) at ensiling or applied (at feedout) to the resultant silages (made without additive) improved aerobic stability, and including hydrochloric acid (to reduce pH and thus increase the undissociated nature of the caproic acid) conferred no measurable benefits. When caproic acid was applied at 1.2 and 6.0 g/kg the low rate greatly extended aerobic stability while the high rate prevented aerobic deterioration, and the effects were greater when the additives were applied at ensiling rather than at feedout (Ohyama *et al.*, 1977).

Woolford (1978) evaluated the effects of ammonium isobutyrate and concluded that although it might protect silage from aerobic deterioration the amount required for low DM silage was likely to be excessive.

<u>Mixture of acids</u>. For a variety of reasons mixtures of acid or acid-based compounds are used as silage additives. Table 2 summarises a series of eight laboratory silo experiments

comparing unwilted grass ensiled with no additive, formic acid (850 g/kg; density 1.192 kg/l; applied at 3 ml/kg) or a partially neutralized blend of aliphatic organic acids (860 g ammonium formate, 100 g ammonium propionate and 20 g caprylic acid/kg; density 1.172; applied at 6 ml/kg). Within each experiment there were four silos per treatment. Although the effects of the additives on aerobic stability (duration until pH or temperature rose) were not significant ($P>0.05$) the extent of aerobic deterioration (accumulated temperature rise) was halved by the blend of aliphatic organic acids. Thus,

Table 2. Silage fermentation and aerobic stability and deterioration characteristics - statistical summary of eight laboratory silo experiments at Teagasc Grange comparing unwilted grass ensiled with no additive (NA), formic acid (FA) or a partially neutralized blend of aliphatic organic acids (Mx)

Additive	pH	NH_3-N g/kgN	Days to pH rise	Days to ^{O}C rise	Acc. ^{O}C rise to day 5[1]
NA	4.49	121	3.5	2.8	49
FA	4.28	78	3.8	2.6	43
Mx	4.29	91	5.4	2.9	22
sem	0.101	7.8	0.49	0.11	6.9
Sig.	0.278	0.005	0.033	0.321	0.034

[1]Accumulated ^{O}C rise to day 5

whereas the duration of aerobic stability was not altered, the extent of subsequent deterioration once instability commenced was greatly restricted by the blend of organic acids.

Improvements in aerobic stability have been widely reported in response to applying mixtures of organic acids to forage pre-ensiling – e.g. Stryszewska and Pys (2006; 0.59 formic acid + 0.2 propionic acid + 0.043 ammonium formate + 0.0255 potassium sorbate) and Randby (2002; 0.64 formic acid + 0.093 propionic acid + 0.019 benzoic acid). O'Kiely *et al.* (2007) applied a mixture of formic acid, ammonium formate, propionic acid, benzoic acid and ethyl benzoate (A1) or a mixture of acetic acid and iso-butyric acid (A2) to a series of harvests of high-moisture wheat and barley grain, and more frequently recorded aerobic stability benefits for A1 compared to A2. Adesogan *et al.* (2003) recorded similarly beneficial effects when A1 was applied at ensiling to high-moisture wheat grain. In contrast to the above, Lorenzo and O'Kiely (2008) recorded either no benefit or a disimprovement in aerobic deterioration when a mixture of potassium formate (0.82) + sodium bisulphate (0.1) + sodium benzoate (0.07) was applied (at 3 g/kg) to grasses at ensiling.

Ohyama and McDonald (1975) showed that under conditions where formic acid stimulated aerobic deterioration then including isovaleric acid or caproic acid with formic acid prevented the deterioration while including lauric acid provided no such benefit [3.8 g of each acid added to 15 g formic acid and applied to 1 kgDM].

Ohyama and Hara (1979) evaluated a mixture of calcium formate (0.75) + sodium benzoate (0.1) + sodium bisulphite (0.1) + minerals (0.05) [applied at 2.5 g/kg forage maize pre- or post-ensiling] and found only a relatively small benefit to aerobic stability from applying the additive at ensiling but a substantial benefit form applying it to the silage at feedout.

2.2 Aldehydes

Woolford (1975b) evaluated the anti-mycotic effects of both formaldehyde and paraformaldehyde and found a markedly greater effect with formaldehyde. Ohyama and McDonald (1975) confirmed that applying formaldehyde to wilted grass (at 6.9 g/kg) inhibited yeast activity and produced aerobically stable silage. Hexamine (hexamethylenetetramine) releases formaldehyde under acidic conditions and Woolford (1975b) found it to be much less anti-mycotic than paraformaldehyde at pH 6 or 5, but to be equally anti-mycotic as formaldehyde at pH 4. These compounds are not used as the sole ingredients in silage additives, and only hexamine has been used to any extent in recent years. It has most frequently been combined with sodium nitrite, as well as with some other salts.

3. Inorganic chemical additives

3.1 Acids

Sulphuric acid (450 g/kg) has been used as a lower cost alternative to formic acid when seeking to achieve satisfactory silage preservation. However, it is less inhibitory in its anti-microbial effects than formic acid. Using immature forage maize, O'Kiely (1998a) showed that whereas aerobic stability was improved and aerobic deterioration reduced by formic acid (850 g/kg; applied at 3 ml/kg), the reverse outcome occurred when sulphuric acid (applied at 3 ml/kg) was used. O'Kiely (1997a) applied sulphuric acid at 0, 1.5, 3.0, 4.5 and 6.0 ml/kg and found that even though the 4.5 and 6.0 ml/kg application rates progressively reduced aerobic deterioration, the biological magnitude of this statistically significant effect was relatively small. Thus, sulphuric acid applied alone has little to contribute to providing aerobically more stable silage.

The above agrees with Woolford (1978) who evaluated the anti-microbial effects of hydrochloric acid, orthophosphoric acid, sulphuric acid and sulphamic acid and, other than their direct pH effect, found little direct inhibition of deleterious yeast, mould or bacteria.

3.2 Alkali

Ammonia has strong anti-microbial characteristics, being particularly effective against yeast and mould. Its use as a silage additive is generally restricted to crops with a high content of fermentable substrate and a low buffering capacity (e.g. forage maize), usually of moderately high DM content, since these will readily undergo a lactic acid dominant fermentation and where it is most unlikely that the alkali effect of ammonia will neutralize an excessive proportion of lactic acid and thus promote a clostridial fermentation. Under these conditions (chopped forage maize of approximately 350 gDM/kg) the addition of 1% ammonia at ensiling prevented aerobic deterioration when silage was exposed to air at feedout (Glewen and Young, 1982). Similarly, Buchanan-Smith (1982) recorded a large benefit from cold flow ammonia treatment (+1% on a DM basis) of forage maize ensiled at 280 and 420 gDM/kg, while Phillip *et al.* (1985) reported benefits with high-moisture ear maize (+1% to fresh weight).

Urea can be used as an indirect source of ammonia due to the ubiquitous availability of urease on ensiled forage. This has been shown to improve the aerobic stability of maize or whole-crop cereal silage (Pahlow, 1979; Stacey *et al.*, 2001), and O'Kiely (1998a) repeated these effects (using 3 g urea/kg forage maize) when even immature (182 gDM/kg) maize was ensiled. However, the effects of urea treatment are not universally guaranteed and Pedroso *et al.* (2008) recorded no benefit when urea (5 g/kg) was applied to sugarcane pre-ensiling.

3.3 Other chemical agents

Propylene oxide had relatively weak anti-mycotic effects (less than paraformaldehyde) whereas pimiracin (anti-mycotic), tylosin (anti-bacterial) and bronopol (synthetic anti-microbial) were effective at inhibiting yeast and mould activity in a laboratory assay (Woolford, 1975b). Woolford and Cook (1978) added the anti-mycotic pimaricin and the anti-bacterial chlorotetracycline + chloramphenicol + streptomycin B + bacitracin C + polymyxin B + rose bengal alone or as a mixture to maize silage (i.e. at feedout), and reduced heating only with the anti-bacterial product. However, the use of such compounds in commercial silage additives is unlikely.

Woolford (1978) concluded that chlorine dioxide and sodium formaldehyde bisulphite were unlikely to have a role inhibiting yeast and mould activity in silage. Sodium bisulphite had the ability to limit yeast and mould growth at pH 4, but Woolford (1978) speculated that a high rate of application would be necessary in practice.

When sodium metabisulphite is added to herbage at ensiling it reacts with moisture or acids, releasing SO_2 (beneficially scavenging O_2 in the process) and salts of the acids. Woolford (1978) showed it has potential to reduce yeast and mould growth, particularly at pH 4, but Kleinschmit *et al.* (2005) detected no aerobic stability benefit with maize silage made using a mixture of sodium metabisulphite and amylase.

Sulphite salts in a mixture with lactic acid bacteria (Regulator Live [Thomas & Fontaine Ltd., London] at 1 ml/kg), as well as quebracho tannins, were investigated by Adesogan and Salawu (2002). Using pea/wheat bi-crops these authors found no benefits to silage aerobic stability from applying these products pre-ensiling. This agrees with the findings of O'Kiely *et al.* (1997) who applied sulphites (Regulator [Thomas & Fontaine Ltd., London]) to grass and immature maize at ensiling (at up to 0.4 ml/kg) and found no improvement in silage aerobic stability or reduction in aerobic deterioration – in the case of grass this outcome occurred following 0, 24 and 48 h durations of wilting and where silos were sealed after a 0 or 24 h delay. Since the anti-mycotic effects of sulphites are pH dependent, O'Kiely (1997a) ensiled grasses at pH 5.3, 5.0, 4.5, 3.9 and 3.2 (following addition of sulphuric acid at 0, 1.5, 3.0, 4.5 or 6.0 ml/kg, respectively) but recorded no benefit to aerobic stability from sulphites (and no interaction between herbage pH at ensiling and the application of sulphites). When forage maize of high starch content was treated with sulphites pre- or post-ensiling (at up to 1.2 ml/kg) the additive considerably reduced aerobic deterioration when intimately mixed with silage at feedout but had a lesser or no effect when applied pre-ensiling (O'Kiely, 1998b). The benefits of applying the sulphites-based additive to silage was confirmed for a series of grass and maize silages by O'Kiely (1996), with the effects being largest with the aerobically least stable silages and with an application rate of 4 ml/kg appearing adequate. At this rate of application a negative impact on subsequent rumen digestion would not be anticipated, but such effects could occur at or above 1.2 ml/kg silage (O'Kiely and Moloney, 1997).

Although sodium nitrite has been used as a food preservative, it was much less effective against yeast and less effective against mould (on a molar basis) than potassium sorbate or sodium benzoate in the study of Woolford (1975b). Nevertheless, its anti-mycotic effect increased with a reduction in pH. Sodium nitrite is usually used in combination with hexamine, calcium formate or other compounds, and the nitrite component can degrade during ensilage. Lingvall and Lattemae (1999) sought to identify the optimal application rate of additives containing hexamine and sodium nitrite together with sodium benzoate and sodium propionate, and concluded that the mixture of hexamine and sodium nitrite was unreliable at producing aerobically stable silage when sodium benzoate was included at only 400 g/tonne herbage. However, stability was achieved by the inclusion of sodium benzoate at 800 g/tonne or by 690 g sodium benzoate + 210 g sodium propionate per tonne. In agreement with these findings, Conaghan *et al.* (2009) concluded that a mixture of 80 g hexamine + 120 g sodium nitrite + 150 g sodium benzoate + 50 g sodium benzoate (total density 1.17 g/ml) needed to be applied to wilted grass at 5.0 rather than 2.5 ml/kg to ensure aerobic stability, while McEniry *et al.* (2007) recorded a significant benefit with wilted grass when this additive was applied at 3 ml/kg. However, occasions do occur when this mixture does not give a marked improvement in aerobic stability (O'Kiely *et al.*, 2006). That much of the aerobic stability enhancing effect comes from compounds such as sorbate, benzoate or propionate rather than from hexamine + sodium nitrite was suggested by Ohyama *et al.* (1975) (who used propionate).

Sodium chloride applied at the equivalent of up to 35 g/kg showed little ability to limit yeast or mould growth (Woolford, 1978), and the results of O'Kiely (1996) confirm the absence of an effect on silage aerobic stability or deterioration when NaCl was applied (2 or 4 g/kg) to silage at feedout. However, whereas Harpur *et al.* (1999) also found no benefit from adding NaCl at 10 g/kg silage, they recorded a progressive improvement from mixing NaCl at 20, 30 and 40 g/kg silage. Similarly, O'Kiely and O'Brien (2007) did not obtain a significant reduction in aerobic deterioration by adding NaCl at 8.3 g/kg silage but minimized deterioration with rates of ≥16.7 g/kg silage.

4. Feedstuffs

Sugar-rich materials are sometimes co-ensiled with forage to influence silage preservation, effluent production or nutritive value. A range of outcomes have ensued, with glucose, sucrose or molasses having little impact on subsequent aerobic stability (Nkosi *et al.*, 2009; O'Kiely, 1997b; O'Kiely *et al.*, 2000; O'Kiely and O'Brien, 2007) or improving aerobic stability/deterioration (Arbabi and Ghoorchi, 2008; McEniry *et al.*, 2007; O'Kiely, 1998a), and with materials such as unmolassed or molassed beet pulp and citrus pulp being associated with a disimprovement (Cummins *et al.*, 2007; O'Kiely, 1992; O'Kiely 2002b), no effect (O'Kiely, 1992; O'Kiely, 2002a; O'Kiely, 2002b) or an improvement (Arbabi *et al.*, 2008; O'Kiely and Moloney, 1999) in aerobic stability/deterioration variables. Among other ingredients, applying a blend of essential oils to forage maize at ensiling had little effect on aerobic stability (Kung *et al.*, 2008).

Silages are often mixed with concentrate feeds immediately prior to feeding livestock. This fully exposes the silage to air as well as potentially providing more respirable substrate or aerobic microbial inoculum. When a range of energy- and protein-rich concentrate feeds (wheat, barley, maize, beet pulp, citrus pulp, molasses, soyabean meal, maize gluten, sunflower meal, rapeseed meal, distillers grains and sunflower oil) were individually mixed with an aerobically unstable well preserved grass silage (at 67 g/kg) they had no impact on the aerobic stability/deterioration of the mixture (O'Kiely, *et al.*, 2001). However, when a concentrate feed (498 g barley, 120 g soyabean meal, 100 g palm kernel expeller meal, 125 g citrus pulp, 80 g maize gluten, 50 g molasses, 25 g mineral/vitamin premix. and 2 g oil blend/kg) was mixed (75 g/kg) with ten different grass silages the outcome was that whereas the concentrates did not make silage aerobically more unstable, once deterioration commenced they increased the extent of deterioration (they provided more respirable substrate) (O'Kiely, 2007). In order to determine the impact of the form of the grain, Clancy *et al.* (2000) mixed a series of rates (67, 133 and 200 g grain/kg silage) of five forms of wheat grain (whole grain, rolled grain, milled grain (2mm apertures in sieve), NaOH-treated whole grain (30 g NaOH/kg grain) and urea-treated whole grain (30 g urea/kg grain)) with an aerobically stable and unstable silage. Silage aerobic stability was not compromised by the addition of whole grain, however rolling and milling grain increased the extent of aerobic deterioration without shortening the duration until heating commenced. NaOH-treated whole grain resulted in at least as much aerobic deterioration (i.e. heating) in the silage + grain mixture as had rolled and milled grains, but without altering the initial duration of aerobic stability. Urea-treated whole grain improved aerobic stability when mixed with aerobically unstable silage and increased the extent of aerobic deterioration with the aerobically stable silage.

Overall, the above results suggest that mixing energy- or protein-rich feeds with silage does not shorten the duration until the mixture starts to heat (compared to the same silage after 'mixing' but with no other feed added) – thus, aerobic stability is not shortened. However, once deterioration commences then the overall extent of heating increases due to the greater amount of readily respirable substrate present. This suggests that the supply of readily respirable substrate in silage is not a factor impacting on the aerobic stability of that silage (i.e. most silages already have enough readily respirable substrate to support measurable heating). It also suggests that, because the provision of aerobic microbial inoculum on the concentrate feed does not initiate deterioration sooner, the aerobic stability of the silage was not due to a simple shortage of indigenous micro-organisms capable of respiring substrate.

Sodium bicarbonate is sometimes included in TMRs that include silage and are constituted immediately before feeding. Harpur *et al.* (1999) mixed sodium bicarbonate with grass silage at 0, 10, 20, 30 and 40 g/kg - besides increasing silage pH, sodium bicarbonate also made it aerobically less stable although the effect was progressively less amplified at the two higher rates of addition (the general increase in instability was likely due to the rise in pH; the progressive lessening in the rise in instability was probably due to the corresponding reduction in water activity). In contrast, the same authors found that whereas applying sodium hydroxide at 10 g/kg silage disimproved aerobic stability, increasing the application to 40 g/kg silage prevented aerobic deterioration for 7 days. Bolsen (1981) reported that adding NaOH (+12.2 kg/tonne sorghum at ensiling) improved aerobic stability.

Although O'Kiely (1991) found that mixing (35g/kg) a mineral + vitamin mixture with grass at ensiling ultimately reduced the extent of aerobic deterioration during feedout, this effect was mediated through a major disimprovement in silage preservation and thus would not be a viable option in farm practice.

5. Final comment

- The optimum application rate of a chemical additive that will restrict or inhibit aerobic deterioration of silage is not a constant value. It changes with a range of factors and depends on the scale and nature of the aerobic stability challenge presented by a particular silage under prevailing management and environmental conditions.

6. References

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