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Microbial Inoculation to High Moisture Plant By-Product Silage: A Review

Bhutikini D. Nkosi, Cyprial N. Ncobela, Ronald S. Thomas, Ingrid M.M. Malebana, Francuois Müller, Sergio Álvarez and Robin Meeske

Abstract

Use of microbial inoculants during silage making have drawn interest to silage producers including those who are feeding their livestock on silage produced from by-products (e.g. pulps). Many farmers in the developing countries rely on agro-industrial by-products to feed their livestock, which is limited by the high moisture content of the by-products. This review pertains to issues related to silage production from high moisture plant by-products (e.g. pulps or pomaces), challenges involved in the ensiling of these resources, the use of additives (e.g. microbial additives), and growth performance of the animals that are fed silage from these resources. This information will be helpful to better understand the key roles of silage production from these resources.

Keywords: additives, digestion, forages, inoculation, methane, pulps

1. Introduction

The increasing demand for sustainable animal production is driving animal nutritionists to explore strategies for using high moisture by-products in animal feeding. Several researchers [1, 2] have reviewed the use of agro-industrial by-products as animal feed resources. These by-products are available during food processing and or beverage production, and are often produced in abundance, making it difficult to use them in a short period. Using these by-products in animal feeds will assist the food producing factories to reduce disposal costs while minimising the environmental impacts that these by-products would otherwise create [3].

The high moisture (>25%) content of these by-products makes it difficult to transport and handling during processing and storing [4]. While disposing these by-products might seem as a solution, such an act is associated with potential environmental pollution [5]. Subsequently, the high moisture coupled with high sugar content of these by-products allows for easy contamination by foreign materials and unwanted microbes, which leads to spoilage [1]. Despite the negative factors that are linked with these by-products, they contain valuable nutritional properties such as crude protein, organic matter, fibre and oil [1]. These resources should be processed and stored for animal feeding.

The drying of high moisture by-products to produce meals for animal feeding is technically feasible, but is costly and laborious [6]. Research has shown that ensiling can be an alternative for processing and storing of these resources, provided all basic principles of ensiling are followed [7, 8]. Ensiling entails the preservation of plant/crop resources through anaerobic fermentation, usually by epiphytic bacteria that converts soluble carbohydrates to mainly lactic acid, and minor amounts of volatile fatty acids. The production of organic acids during ensiling reduces the pH to 3.8 to 4.2 for a good quality silage, which inhibits growth of undesirable microbes and results in an ideal preservation on the ensiled material [9]. While ensiling represent an appropriate preservation method for forages, crops and high moisture by-products, it can also result in the losses of nutrients due to undesirable fermentation process in cases where lactic acid is not adequate [10]. To overcome the nutritive losses of the ensiled material, different additives are used.

Additives are constituents that contribute to the reduction of losses, stimulate fermentation, and enrich nutritional value of silage [10]. Such additives include chemicals, enzymes, absorbents and microbial inoculants [11]. Chemical additives such as propionic acid, formic acid, sulphuric acid have been applied to high moisture (> 70% moisture) forages during ensiling for some decades. However, their use in silage is limited due to their toxic nature if not properly applied [10]. Enzymes such as xylanase, cellulase etc. are usually added to forage at ensiling to partially degrade fibre to fermentable water-soluble carbohydrates (WSC) that are consumed by lactic acid bacteria (LAB). The LAB can use fibre as source of energy to produce lactic acid [12]. The use of microbial inoculants ensures rapid and efficient fermentation of WSC to lactic acid and further predicts the adequacy of silage fermentation [13]. Lactic acid bacterial inoculants have been introduced some decades as one of microbial additives that improve forage fermentation, aerobic stability of silage and silage utilization by ruminants [14]. The most commonly LAB inoculants are obligate homofermentative, obligate heterofermentative and facultative heterofermentative LAB [15].

However, it should be noted that the addition of LAB inoculants to forage of low WSC (< 30 g/kg) content, could result to poor fermentation of the forage [16]. Haigh and Parker [17] concluded that WSC content as low as 30 g/kg may be sufficient for a stable fermentation where an effective additive is added during ensiling. In many instances, a source of readily fermentable substrate for LAB is included with commercial bacterial inoculants.

Given that LAB inoculants have been used as silage additives for a long time, their utilization is however more prominent on the ensiling of forages/crops. However, research on the use of LAB inoculants during the ensiling of high moisture by-products is limited. The present study therefore reviewed the use of microbial inoculants on high moisture by-products with special emphasis on silage fermentation and aerobic stability and livestock performance.

2. Addition of high-moisture by-products to improve the ensiling of forages

High moisture by-products such as those from the fruit juice processing contains soluble sugar that can benefit silage making from low sugar forages such as alfalfa. For example, sugar beet pulp [18] and apple pomace [19] contain WSC of 26% and 12% respectively, can be used to improve the fermentation characteristics of silage from low sugar forages. Ke et al. [20] ensiled wilted alfalfa with or without pomaces (i.e. grape and apple) and reported a reduction in silage pH, reduced proteolysis and increased lactic acid production compared to the untreated silage. In contrast, pomace addition reduced silage aerobic stability compared to the untreated silage. Fang et al. [21] added

By-products	Absorbent	Mixture (g/kg DM)		Fermentation response	Aerobic stability	Animal performance/ <i>in vitro</i>	Reference
		DM	WSC				
Apple pomace	Lucerne hay (Alfalfa)	345	7.8	Improved	Reduced	ND	Ke et al. [20]
Citrus pulp	Dehydrated beet pulp	212.8	ND	Not improved	ND	ND	Megias et al. [27]
Orange pulp	Wheat straw	296.6	ND	Improved	ND	IVDMD improved	Paya et al. [28]
	Wheat straw	210.3	ND	Improved	ND	IVDMD reduced	Denek and Can [29]
Sweet potato vines	Sweet potato roots	163	ND	Not improved	ND	IVDMD reduced	Hadgu et al. [30]
Sweet potato vines	Napier grass	197	ND	Not improved	ND	ND	Kabirizi et al. [31]
Potato pulp	Dry rice	269.7	ND	Not improved	ND	ND	Zhang et al. [32]
	Dry bean straw	276.9	ND	Not improved	ND	ND	Zhang et al. [32]
	Dry maize stover	260.0	ND	Not improved	ND	ND	Zhang et al. [32]
Potato hash	Poultry litter	364.0	33.8	Not improved	Reduced	IVOMD improved	Nkosi et al. [33]
	<i>Eragrostis curvula</i> hay	250	22	Improved	Improved	IVOMD improved	Nkosi et al. [33]
Pineapple residue	Poultry litter	234	ND	Improved	Improved	IVOMD reduced	Nhan et al. [34]
Pineapple	Rice polishing	230	ND	Improved	Reduced	Feed intake and weight gain improved	Nhan et al. [34]
Grape pomace	Lucerne hay (alfalfa)	331	7.6	Improved			Ke et al. [20]
Wet sugar beet pulp	Dry pelleted beet pulp	907	ND	Not Improved	Reduced	IVDMD improved	Leupp et al. [35]
Tomato pomace	Ground maize grains	363	ND	Improved	ND	Feed intake improved	Galló et al. [36]
Pumpkin chopped	Dried sugar pulp	292	ND	Improved	ND	ND	Łozicki et al. [37]
	Dried sugar beet pulp	289.6	57.8	Not Improved	ND	ND	Halik et al. [38]
Banana fruit chopped	Dried sugar beet pulp	267.5	ND	Improved	ND	ND	Álvarez et al. [39]
Tomato fruit chopped	Dried sugar beet pulp	263	ND	Improved			Álvarez et al. [40]

By-products	Absorbent	Mixture (g/kg DM)		Fermentation response	Aerobic stability	Animal performance/ <i>in vitro</i>	Reference
		DM	WSC				
Orange pulp	Dried citrus pulp	712	ND	Improved	Improved	IVDMD improved	Arbabi et al. [41]
	Dried sugar beet pulp	707	ND	Improved	Improved	IVDMD improved	Arbabi et al. [41]
	Wheat straw	606	ND	Improved	Improved	IVDMD improved	Arbabi et al. [41]
Apple pomace	Maize plant	213	ND	Improved	ND	IVOMD improved	Ülger et al. [42]
	Sugar beet pulp	151	ND	Improved	ND	IVOMD improved	Ülger et al. [42]
	Pumpkin pulp	115	ND	Not improved	ND	IVOMD improved	Ülger et al. [42]
Sugar beet pulp	Molassed beet pulp	186	249	Improved	Unaffected	IVDMD improved	O’Keily [43]
	Unmolassed beet pulp	188	75	Improved	ND	ND	O’Keily [43]
	Barley	189	18	Improved	ND	ND	O’Keily [43]
Citrus pulp	Wheat bran	124	ND	Improved	Reduced	OMD improved	Kordi and Naserian [44]

ND: Not detected; IVOMD, *in vitro* organic matter digestibility.

Table 1.
Effects of the use of absorbents on fermentation characteristics, aerobic stability and in vitro/ animal performance fed silage from high moisture plant by-products.

0, 5, 10 and 20% apple pomace in a total mixed ration that was ensiled for 90 days, and reported an increased silage ethanol production with the 20% inclusion of apple pomace. This was attributed to the increased sugar content of the silage mixture.

3. Use of absorbents to improve the ensiling of high moisture plant by-products

One of the major setbacks in ensiling agro-industrial by-products is their high moisture contents (>25%) that requires the by-products to be dehydrated or mixed with absorbents to improve the dry matter contents, compaction and ensiling process [22]. When silage DM content is less than 300 g/kg, conditions for clostridial activity are favourable, resulting in high losses and silage of low nutritional value [23]. To enhance the fermentation process and sustain nutritional quality during ensiling, various additives such as feedstuffs, nutrients and absorbents [24, 25], and non-protein nitrogen agents, chemicals and enzymes have been used [26].

High moisture by-products such as pulps and pomaces are difficult to ensile and may lead to seepages, causing nutrient losses. These by-products are usually ensiled with absorbents (i.e. dry sources) to improve both the dry matter and fermentation. The effects of adding various absorbents to high moisture by-products at ensiling are shown in **Table 1**. Adding absorbents to high moisture plant by-products at ensiling improved the fermentation (66%), silage aerobic stability (50%) and in vitro or animal performance by 74% of the responses. This variation in responses depends on the nutritive values and WSC content of the absorbents used. Nkosi et al. [45] ensiled potato hash with either *Eragrostis curvula* hay and poultry litter as absorbents. They reported higher crude protein content in the silage produced with poultry litter than that produced with the grass hay. Migwi et al. [46] ensiled citrus pulp with either straw or poultry litter and reported improved silage fermentation dynamics with these two absorbents. The addition of straw to the beet pulp improved the DM content, WSC, *in vitro* dry matter digestibility (IVDMD) and increased the fibre fraction of the silage compared to the control. Megias et al. [27] and Paya et al. [28] reported that hay and wheat straw improved silage fermentation when used as absorbent in citrus pulp silage. Islam et al. [47] reported that wheat bran and wheat straw did not improve silage fermentation when used as absorbent in apple pomace silage. Zhang et al. [32] further reported that dry rice; dry beans and dry corn stover did not improve silage fermentation when used as silage absorbent when ensiling potato pulp. Khattab et al. [48] ensiled banana wastes mixed with wheat straw and broiler litter. The silage was treated with either diluted molasses or sweet whey as nutrient (sugars) additives, which improved growth performance of buffaloes. The addition of *Eragrostis curvula* hay as an absorbent did not improve the quality of the potato hash silage [49]. Álvarez et al. [40] ensiled tomato fruit mixed with either dehydrated beet pulp or cereal straw and reported improved nutrient content in silage mixed with dehydrated beet pulp. Hadjipanayiotou [50] added either poultry litter or straw to tomato pulp silage and reported greater CP content in silage treated with poultry litter compared to the straw treated silage.

4. Use of microbial inoculants during the ensiling of high moisture by-products

4.1 Microbial inoculants

Microbial inoculants are products that are added or inoculated to forages to increase the number of microbes (e.g. LAB) in the forage at ensiling and influence

the fermentation process of the forage in the silo [51]. The forage at ensiling is generally dominated by aerobic micro-organisms or facultative aerobes, with less population of LAB [52]. Forages are usually inoculated with homofermentative and facultative heterofermentative LAB to enhance LA fermentation of forages. Homofermentative LAB produces 2 moles of lactic acid from one mole of glucose, and these products contain strains species such as *Lactobacillus* (e.g. *planturum*, *pediococcus* species, and *enterococcus* species) [52] and the recent meta-analysis by Oliviera et al. [53] showed *Lactobacillus planturum* as the mostly used species. Heterofermenters produces one mole of lactic acid, one mole of carbon dioxide and one mole of acetic acid [52]. Homofermentative LAB are reported to yield high DM recovery and little energy loss from the silage while the heterofermentative LAB results in high DM losses, increase in silage pH and volatile fatty acids such as acetic and propionic acids [54]. According to Avila et al. [55] facultative heterofermentative LAB strains are not good for producing sugarcane silages due to increased DM losses. However, inoculation of forages with heterofermentative LAB increase the concentration of acetic acid or propionic acid, which are suitable for yeast control because of their fungicidal effect [56]. This means that heterofermentative LAB inoculants improve the aerobic stability of silage while it can be reduced with Homofermentative LAB inoculation [51, 57]. According to Muck [52] the rumen bacteria ferment lactic acid whereas acetic acid is a product of rumen fermentation. Hence there are benefits to rumen microbial growth from producing lactic acid from the silo during ensiling of forages. In a recent meta-analysis on the inoculation rates of LAB to forages, the 10^6 colony forming units (CFU)/g was common, and the 10^5 and 10^6 cfu/g inoculation rates were most effective for improving silage fermentation, reducing acetic acid production and improving DM recovery [53]. This study further reported that the recommended inoculation rate for silage inoculants varies by region, with 10^5 cfu/g being common in the United States, 10^6 cfu/g in Europe, and 10^4 cfu/g being common in some Asian and South American countries. The type of forage was the most consistent factor affecting the silage quality response to LAB inoculation [53]. With cereal grain forages such as corn, the lack of response with LAB inoculation is probably because these forages contained sufficient WSC, epiphytic bacterial population and low buffering capacity.

4.2 Silage fermentation characteristics

Bouillant and Crolbois first adopted the principle of microbial inoculation in 1909 when they applied LAB inoculants to beet pulp to improve fermentation [58]. Later in 1934, Rushmann and Meyer (1979, were cited by [59]) documented that the rate of acidification during silage fermentation is dependent on epiphytic bacteria found on forages. Currently, there are several silage inoculants available on the market with inoculation rate that ranges between 10^4 and 10^6 colony forming unit (CFU)/g [60]. Most commercially available inoculants contain homofermentative LABs, which are fast and efficient producers of lactic acid, and thus improve the silage fermentation. However, these LAB inoculants are mostly designed/produced to be used in the ensiling of forages to ensure enough LAB inoculation at ensiling. Most studies (e.g. [61, 62]) showed an increased in LAB population when LAB inoculants were applied to forages at ensiling. The response to LAB and enzyme inoculation to various high moisture by-products at ensiling are presented in **Table 2**. Literature shows that the response to LAB inoculation to forage varies a lot. Some reported positive effects in the terms of fermentation dynamics while some reported lack of response. LAB inoculation to high moisture by-products at ensiling have underwent the same pattern as with the forages. For instance, Parigi-Bini et al. [68] found that the inoculation of lactobacilli (*Lactobacillus plantarum* and

By-Product	Treatment			Fermentation	LAB type	Inoculation rate	Ensiling days	Reference
	Parameter	Control	Inoculant					
Sugar beet pulp	pH	3.91	3.95	Not improved	<i>L. fermentum</i> nrri b-4524	-	90	Zheng et al. [63]
	LA	33	28.92	Not Improved		-		
	AA	34.69	35.07	Not Improved		-		
Tomato pomace	pH	4.97	4.57	Not Improved	Sill All	10 ⁵ CFU g ⁻¹ diluted with 2L water	70	Galló et al. [36]
	LA	179	20.5	Not Improved				
	AA	9.16	14.2	Not Improved				
Sweet potato vines	pH	4.06	3.84	Improved	<i>(Lactobacillus buchneri, Lactobacillus plantarum and Enterococcus faecium)</i>	1.1 × 10 ¹¹ CFU/g		Yacout et al. [64]
	LA	47.1	51.3	Improved				
	AA	31.7	33.2	Improved				
Orange pulp	pH	3.8	3.5	Improved	<i>Lactobacillus Plantarum</i>	1 g/kg diluted with 50 ml water (700000 U/kg)	90	Paya et al. [28]
	LA	36.4	47.2	Improved				
	AA	9.5	6.85	Not Improved				
Potato hash	pH	3.5	3.14	Improved	Viscozyme® (hemicellulose and pectinase from <i>Aspergillus spp</i>)	100 ml enzyme diluted with 1 l of water	90	Nkosi et al. [45] Mutavhatsindi et al. [65]
	LA	58.3	71.7	Improved				
	AA	6.3	3.4	Improved				
	pH	3.8	3.7	Improved	Enzymes (celluclast)	-		
	LA	36.42	41.25	Improved				
	AA	9.50	14.47	Improved				

By-Product	Treatment		Fermentation	LAB type	Inoculation rate	Ensiling days	Reference
	Parameter	Control	Inoculant				
Potato pulp	pH	3.97	3.94	Improved	<i>Rhizopus oryzae</i>	1×10^6 CFU g ⁻¹	Okine et al. [66]
	LA	24.6	26.8	Improved			
	AA	10.6	12.6	Improved			
	pH	3.97	3.95	Improved	<i>Amylomyces rouxii</i>	1×10^6 CFU g ⁻¹	
	LA	24.6	24.8	Improved			
	AA	10.6	10.0	Improved			
Peach pomace TMR	pH	4.29	4.24	Not Improved	<i>Pediococcus acidilactici</i> , <i>Lactobacillus buchneri</i>	- 3×10^5 CFU g ⁻¹	Hu et al. [18]
	LA	71.1	62.1	Not Improved			
	AA	13.8	9.0	Not Improved			
Potato hash TMR	pH	4.3	4.1	Improved	Lalsil fresh	-	Nkosi et al. [67]
	LA	61.0	69.8	Improved			
	AA	31.8	36.3	Improved			
Pumpkin chopped	pH	3.96	3.78	Improved	Bacterial-enzyme- <i>Lactobacillus plantarum</i>	2×10^9 CFU g ⁻¹	Łozicki et al. [37]
	LA	56.4	64.3	Improved			

Table 2.
Effects of LAB inoculation on fermentation of high moisture plant by-products silage.

Streptococcus) to pressed sugar beet pulp did not affect the nutritional value and fermentation of the silage. Similarly, Okine et al. [66] ensiled a daikon by-product with or without *L. plantarum* and reported no effect on fermentation characteristics of the silage. In contrast, Okine et al. [69] ensiled potato pulp with bacterial inoculants (*Lactobacillus rhamnosus*) alone, *Rhizopus oryzae* alone and their combinations, and reported reduced content of the main carbohydrates, starch and pectin in the pulp with bacterial inoculation. **Table 2** shows that 63% of the responses in this review were positive towards LAB inoculation to high moisture by-products at ensiling.

4.3 Aerobic stability of silage

The aerobic stability is a term that nutritionists have used to define the length of time that silage remains cool and does not spoil after it is exposed to air [70]. The aerobic deterioration of silage may increase the risk of proliferation of potential pathogenic or undesirable microorganisms thus affecting the performance of animals fed the silage. In most cases, aerobic deterioration of silage happens with silages that contain high residual sugars [14]. It is noteworthy that *Lactobacillus buchneri* (LB), a heterofermentative LAB inoculant [51, 57] have been reported to improve the aerobic stability of silages due to increased acetic acid production. Previous research with potato hash silage [49, 71] showed improved aerobic stability of silage with LB inoculation. Li et al. [72] ensiled a mixture of corn steep liquor with wheat straw and treated with either heterofermentative or homofermentative LAB. They reported an increase in acetic acid content and improved aerobic stability of silage with heterofermentative LAB compared to untreated silage. The inoculation of LB during the ensiling of forages is often criticised due to increase in silage pH, acetic acid and losses in DM and energy [12, 15, 56, 73–80]. However, if aerobic stability is improved, the loss of nutrients incurred by the addition of LB may be moderate in comparison with what might have been lost at feed out through aerobic deterioration [71].

5. Effects of microbial inoculation to ensiled totally mixed rations (TMRs) on fermentation and aerobic stability

Due to the high moisture content in fresh high moisture by-products, it is more advantageous to mix them with other dry feed materials before ensiling. This technique helps to omit the time of mixing before feeding, minimize the risk of effluent production and avoids self-selection of feeds by animals [81, 82]. In some studies, TMRs that contained high moisture by-products (e.g. [83]) [49] were formulated and ensiled. Nkosi and Meeske [71] reported an improved silage fermentation, aerobic stability and animal growth performance when TMR that contained potato hash was treated with LAB inoculant. However, Nishino and Hattori [83] reported improved silage fermentation but LAB inoculation was not worth in the aerobic stability of TMR silage. This might be attributed to the addition of various feed ingredients that might have helped to stabilize the TMR silage.

6. Animal performance

The production of silage will not be worth if it is rejected by animals during the feeding out phase. Animal performance includes feed intake, feed palatability, nutrient digestion, daily gains, milk and meat production. The results on the performance of animals fed plant by-product silage treated with LAB varies like when animals are fed LAB treated silages from plants/forages. According to **Table 3**,

By-products	LAB type	Inoculation rate	Animal species/ <i>in vitro</i>	Response	Reference
Potato hash	Bonsilage forte (<i>Lactobacillus paracasei</i> , <i>Lactobacillus lactis</i> , <i>Pediococcus acidilactici</i> and Lalsil Fresh LB (<i>Lactobacillus buchneri</i>))	2.5×10^5 CFU g ⁻¹	Mutton Merino rams	Improved gross energy, crude protein and fibre digestibility. Improved nitrogen intake and retention.	Nkosi et al. [49]
Spent mushroom substrate	Mixture of <i>Enterobacter ludwigii</i> KU201-3, <i>Bacillus cereus</i> KU206-3, <i>Bacillus subtilis</i> KU3, <i>Bacillus subtilis</i> KU201-7, <i>Saccharomyces cerevisiae</i> , and <i>Lactobacillus plantarum</i>	1×10^9 CFU g ⁻¹	Cross bred rams	Improved EE digestibility and nitrogen retention.	Seok et al. [84]
Spent mushroom substrate	<i>Enterobacter ludwigii</i> KU201-3, <i>Bacillus cereus</i> KU206-3, <i>Bacillus subtilis</i> KU3, <i>Saccharomyces cerevisiae</i> , and <i>Lactobacillus plantarum</i>	Each strain at 0.12% v/w	Hanwoo steers	Improved ADG, FCR and FI	Kim et al. [85]
Tomato pomace	Sil All 4x4 (<i>Enterococcus faecium</i> , <i>Pediococcus acidilactici</i> , <i>Lactobacillus plantarum</i> , <i>Lactobacillus salivarius</i>)	1×10^5 CFU g ⁻¹	Game	Improved	Galló et al. [36]
Sugar beet pulp	Sil add (<i>Lactobacillus plantarum</i> , <i>Pediococcus acidilactici</i> , <i>Streptococcus bovis</i> and <i>Selenomonas ruminantium</i>)	0.5 g/kg FM basis	Hereford and Friesian steers	Unaffected	O'Keily [43]
Chinese cabbage	<i>Lactobacillus plantarum</i>	5 mg/kg FM basis	<i>In vitro</i>	Increased DM digestibility.	Cao et al. [7]
Cabbage waste	Silobac® (<i>Lactobacillus plantarum</i> and <i>Pediococcus pentosaceus</i>)	5×10^5 CFU g ⁻¹	<i>In vitro</i>	Increased DM digestibility.	De Rezende et al. [86]
Yacon (<i>Smallanthus sonchifolius</i>)	Chikuso-1 (<i>Lactobacillus plantarum</i>)	5 mg/kg FM basis	<i>In vitro</i>	Increased DM digestibility.	Wang et al. [82]
Avocado pulp	Emsilage® and Sil-All®	3.5×10^5 CFU g ⁻¹	<i>In Vitro</i>	Improved silage degradation	Nkosi et al. [87]

Table 3.
Effects of microbial inoculation to high moisture plant by-product silage on animal growth performance.

LAB inoculation to high moisture plant by-products improved animal performance in almost all the literature consulted, except for the sugar beet pulp silage reported by O'Keily [43]. It is well known that improved performance by animals fed LAB treated silages are difficult to explain [26]. However, Weinberg et al. [88] suggested that the interaction of LAB and rumen microbes and the alteration of LAB and rumen fermentation might be attributed to the improvement of animal performance with LAB treated silages.

Inoculation of potato hash silage with *L. buchneri* did not change the DM or organic matter (OM), but bonsilage forte inoculation improved digestibility of ether extract and increased nitrogen (N) intake and retention in sheep fed the silage [49]. Further, Thomas et al. [89] compared the effects of two bacterial inoculants on digestibility, growth performance and carcass characteristics of growing pigs fed the ensiled potato hash, and reported no improvement with LAB inoculation on the growth performance and meat characteristics of growing pigs. Okine et al. [69] ensiled potato pulp with *L. rhamnosus* and *Rhizopus oryzae*, and reported lack of influence from LAB inoculation on the digestibility of the silage by ruminants. In contrast, Li et al. [72] treated corn steep liquor silage with LAB and reported improved DM digestibility, which resulted in less methane production compared to untreated silage. Further, a study by Pulido et al. [90] showed an improvement in the nutritive value of sugar beef pulp silage with LAB inoculation, which increased milk production from dairy cows by 2%, though milk composition was not affected by the inoculation.

Methane, a greenhouse gas produced from enteric fermentation in the rumen, is a major concern in ruminant production globally. It is well indicated that by improving forage quality and digestibility, this gas production can be reduced. In terms of reduction gas production with LAB inoculation, very few studies have tested this effect in silages from high moisture by-products. Cao et al. [7] reported a reduced gas production with *L. plantarum* inoculated to vegetable residue silage, which suggest that LAB inoculation can be effective in reducing gas emission in silages. However, Ellis et al. [91] have cautioned that LAB inoculation to forage will not always give positive response. They mentioned that the strain and dose differences, different basal silages and ensiling conditions might be responsible for the variability in responses from LAB inoculation.

7. Properties required in high moisture plant by-products for efficient silage fermentation

As indicated earlier, the low DM content in high moisture plant by-products is a concern since it can promote a clostridial type of fermentation if not improved prior to ensiling. According to Muck [52], most silages are produced at DM content that ranges from 300 to 500 g/kg, hence the DM of these by-products should be increased. This can be achieved by mixing with absorbents/dry forages. Also, the success of ensiling is determined by various factors that include the anaerobic conditions in the silo, WSC content, the buffering capacity of the pre-ensiled forage, and the epiphytic bacteria. Bacterial inoculation will be worthless if the by-products contain insufficient sugars, which should be consumed by LAB to produce lactic acid, which will reduce silage pH and preserve the crop [23].

8. Conclusion

Good quality silage can be produced from high moisture plant by-products with or without LAB inoculation. Increasing the DM content of high moisture plant

by-products to >30% is required for efficient fermentation. It should be noted that there are no specific LAB inoculants designed for inoculation to high moisture plant by-products. The efficacy of LAB inoculation to forages depends highly on the type of crop/by-product, the strain and different doses and the ensiling management.

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