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Review

Ensiling of High-Moisture Plant By-Products: Fermentation Quality, Nutritional Values, and Animal Performance

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Abstract: Animal feeds under ruminant production are a challenge, and ruminants are mostly fed on fibrous plants including high-moisture plant by-products (HMPBs). These HMPBs are available during the food processing periods and cannot be fed entirely in their fresh form. These resources are conserved in the form of silage for future feeding. Silage-making entails the anaerobic preservation of forages with the aid of additives that reduce the pH of the ensiled materials and preserve the forage. Most silage research work focuses mainly on the preservation of forages/plants, with less attention on HMPBs. This review focuses on the silage production from HMPBs (e.g., pulps/pomaces), challenges involved in the ensiling of these resources, use of additives (e.g., chemical additives), and growth performance of ruminants fed silage from these resources. This review will assist farmers from developing countries who rely on HMPBs as sources of animal feed.

Keywords: additives; ensiling; fermentation; pomace; pulps; ruminant

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1. Introduction

High-moisture plant by-products (HMPBs) are waste materials derived from the production of food (e.g., beverages, juice, wine, etc.) in factories. These HMPBs contain nutrients that can benefit livestock production [1]. The incorporation of HMPB animal rations has been practiced for some decades and has proven to be a successful substitute for conventional feed ingredients (e.g., corn, barley, etc.) [2]. Feeding HMPBs to livestock is a common practice done by livestock producers who are in areas located near the food or wine/juice production industries. However, because of their high moisture (i.e., >750 g moisture/kg) and the presence of monosaccharides, the storage life of many HMPBs is short, depending primarily on the environmental temperatures. Although the drying of HMPBs to produce meals is a possible technique, it requires sufficient solar radiation or the use of sophisticated drying facilities, of which the latter might not be achievable during the rainy season and the former is costly [3]. It should be noted that the sugar content in HMPBs might vary depending on the season, variety, maturity period, location of the cultivation of the fruit, and food/wine processing methods [4].

Ensiling of HMPBs requires anaerobic conditions whereby the epiphytic lactic acid bacteria (LAB) will grow to produce lactic acid (LA) and reduce the pH of the ensiled material [5]. This process generally controls microbial activity by the combination of an anaerobic environment and a natural fermentation of sugars by LAB on the crop [6]. One of the advantages of ensiling HMPBs is that some anti-nutritional agents (e.g., trypsin inhibitors) that are present in the HMPBs may be reduced through anaerobic fermentation [7], which improves its utilization by ruminants [8]. There is also an increasing practice worldwide to preserve these by-products with dry feeds/absorbents in the form of totally mixed rations (TMR) [9,10]. This method helps to (i) alleviate energy costs involved with the drying/or production of meal from these by-products, (ii) reduce transporting of HMPBs, (iii) facilitate preservation in silo regardless of the various by-products, and (iv) reduce the unpalatability of by-products by mixing them with other resources e.g., sugarcane molasses. The present study aims to address challenges pertaining to the ensiling of HMPBs, the use of additives (i.e., chemical and microbial), and the growth performance of ruminants fed the HMPBs silage.

2. Dry Matter and Water-Soluble Carbohydrate Contents in Various HMPBs

The success of ensiling is determined by various factors including the anaerobic conditions in the silo, water soluble-carbohydrates (WSC) content, the buffering capacity of the pre-ensiled forage, dry matter (DM) content, and the epiphytic bacteria [6]. Although most HMPBs (e.g., apple, pear, grape pomaces, tomato pulps, etc.) are rich in the content of WSC, one of the challenges associated with ensiling HMPBs is their low DM contents (Table 1), which makes them difficult to ensile. Silages should be produced at a DM content that ranges from 250 to 500 g/kg [6], and if the DM content is less than 250 g/kg, conditions for clostridial activity are promoted, resulting in high nutrient losses and silage of low nutritional value [11]. As a result, absorbents such as forage straws, hay, brans, etc. are added to HMPBs at ensiling to increase the DM content and improve the fermentation quality and nutritive value of the ensiled material. The high moisture content in HMPBs necessitates the use of dry sources for efficient ensiling to avoid a clostridial type of fermentation. Nutrient losses through seepage can be of concern, especially with high-moisture HMPBs.

Table 1. Composition (g/kg DM) of CP, DM, and WSC in high-moisture by-products.

By-Products	Scientific Name	CP	DM	WSC	References
Molasses sugar beet pulp	Beta vulgaris	108–114	100–270	248–252	[12,13]
Cassava pulp	Manihot esculenta	196	188	-	[14]
Potato pulp	Solanum tuberosum	85	188	33.5	[15]
Avocado pulp	Persea americana	78–147	119–186	15.3–62	[16,17]
Tomato pomace	Solanum lycopersicum	195–198	61–269	509	[18–20]
Citrus pulp	Citrus X sinensis	69–92	170	246–412	[1,21]
Grape pulp	Vitis	122	421	19	[16]
Pineapple wastes	Ananas comosus	60	129	40	[22]
Apple pomace	Malus domestica	22	180	125	[23]
Peach pomace	Prunus persica	74	59	259	[24]
Pomegranate pulp	Punica granatum	79	200	175	[16]
Mulberry pomace	Morus	198	270	156	[25]
Ripe banana wastes	Musa	60	213	505	[26]
Sea buckthorn pomace	Hippophae	74	518	411	[27]

CP = crude protein; DM = dry matter; WSC = water-soluble carbohydrates.

3. Absorbents' Effects on HMPBs Silage Fermentation and Nutrient Utilization by Ruminants

Absorbents/dry feeds have different nutrient properties due to their differences in crop/plant varieties, production environments, and drying processes. Adding these resources to HMPBs influences the fermentation characteristics and nutrient composition of the resultant silage. Researchers [7] mixed wet brewers' grains with dried barley straw at 50:50 at ensiling and reported improvement in both the fermentation and in vitro dry matter digestibility (IVDMD) of the silage. This silage supplied 50% total digestible nutrients and 10% digestible crude protein to sheep. Using soybean hulls as absorbents for WBG silage, researchers [28] reported reduced silage fermentation and reduced dry matter intake but improved feed efficiency in heifers. Others [18] compared two absorbents (wheat straw and wheat grain) in the ensiling of tomato pulp, and the dry matter intake by sheep was not affected by the absorbents.

Poultry litter, a by-product from poultry production, is rich in nitrogen (N) and mineral contents. This by-product has been used to increase the dry matter and crude protein content of ensiled materials, but its inclusion negatively affects silage fermentation due to its high buffering capacity. Adding poultry litter to sugar beet pulp increased silage pH, dry matter, crude protein, volatile fatty acids, and ruminal ammonia-N but reduced the crude protein digestibility in adult wethers [29]. Consistently, researchers [30] ensiled citrus pulp with poultry litter and reported increased silage crude protein, pH, and acetic acid while decreasing the concentrations of lactic acid compared to the untreated silage.

Mixing sweet beet pulp with corn stalks (3:1 ratio) resulted in silage containing reduced pH and fiber fractions with increased lactic acid production compared to untreated silage [31]. The researchers reported a reduced production cost with the resultant silage. Adding wheat bran and ground corn to wheat bran grain at ensiling improved the intakes of dry matter and organic matter in dairy cows but did not affect milk production compared to the silage containing soybean hulls [32]. Researchers [33] mixed citrus pulp with wheat bran at ensiling and reported improved crude protein, fiber fractions, organic matter digestibility, and energy with increased wheat bran, but the aerobic stability of the silage was reduced. In contrast, researchers [34] reported improved aerobic stability of banana wastes ensiled with wheat bran due to increased DM and fiber fractions of the silage.

In some instances, dried by-products are added to HMPBs at ensiling. For example, some researchers [35] used sweet beet pulp pellets to ensile wheat bran grain and reported an increase in silage dry matter with reduced crude protein and fiber fractions compared to other treatments that did not contain sugar beet pellets. In addition, other researchers [36] reported improved silage fermentation and reduced aerobic stability of the silage when pelleted citrus pulp was added to citrus pulp at ensiling. This was due to the increased production of residual sugars known to be nutrients for aerobic microbes during the feed-out phase [37].

4. HMPBs as Silage Additives

It is apparent from Table 1 that most HMPBs are rich in fermentable substrates and can be beneficial to the ensiling of forages that are low in soluble sugar contents (e.g., legumes). It should be noted that the WSC content in HMPBs is affected by numerous factors such as fruit variety, ripening stage, physical and chemical properties of the fruit, juice extraction technologies, and various enzyme utilization during extraction [38]. According to researchers [39], the WSC content of 30 g/kg may be sufficient for a stable fermentation and the HMBPs contain more sugar than this threshold (Table 1). Researchers [40] added citrus pulp to alfalfa at ensiling and reported an increased WSC, reduced silage pH and aerobic stability. Adding sea buckthorn (*Hippophae* L. *Eleagnaceae*) pomace (411 g WSC/kg DM) as a fermentable substrate to alfalfa (62 g WSC/kg DM) at ensiling reduced silage pH and ammonia-N but increased residual sugars that reduced silage aerobic stability [27].

Researchers [12] ensiled perennial ryegrass treated with molasses sweet beet pulp and reported improved DM, WSC, and gross energy content but reduced the fiber fractions of the grass silage compared to the control. The dry matter intake and nutrient digestibility were not affected by treatments, but the ruminal pH was reduced while ruminal volatile fatty acids were increased with the sweet beet pulp addition. Adding sweet beet pulp to ryegrass at ensiling increased DM content and silage fermentation while it reduced in-silo effluent production [41]. This was consistent with others [42] who reported improved DM and WSC contents with sweet beet pulp addition in grass. According to these researchers [42], this type of silage has reduced aerobic stability due to lower volatile fatty acids even though it improved the intake by beef cattle compared to untreated grass silage. In contrast, others [43] mixed sweet beet pulp with timothy grass, and no effect on silage fermentation and aerobic stability was observed, although the DM, WSC, and IVDMD were improved. Other researchers [13] also added sweet beet pulp to low DM (150-240 g DM/kg) corn at ensiling and reported increased DM and lactic acid in the silage. Some [44] reported increased methane production when sweet beet pulp was added to yacon (*Smallanthus sonchifolius*; family *Asteraceae*) plant by-product at ensiling. This was due to the increased sugar content of the silage.

Pomaces from grapes and apples have been used to improve the fermentation characteristics of forages at ensiling. For example, researchers [45] reported increased concentrations of lactic acid and oleic and linoleic acids and reduced proteolytic activity in alfalfa silage added with either grape (*Vitis vinifera* L.) pomace or apple (*Malus domestica*) pomace. The addition of these by-products also reduced the aerobic stability of the silage. Moreover, the addition of grape pomace to sweet sorghum at ensiling reduced both silage pH and polyphenol, which leads to tannin inactivation [46]. In some cases, miscellaneous forages were treated with pomaces at ensiling to influence the fermentation quality of the ensiled materials. Researchers [47] ensiled *Calotropis procera* plant that was mixed with grape pomace at ensiling and reported increased ethanol production, volatile fatty acids, effluent production, and gas loss but reduced nutrient digestibility. The reduced nutrient digestibility was related to the increased fiber fraction of the silage that was associated with grape pomace. Adding liquid feedstuffs (i.e., molasses and corn steep liquor) to low-DM (25%) sweet beet pulp improved fermentation of the silage but increased the effluent production [48]. Others [26] ensiled ripe banana wastes with dried sweet beet pulp and reported an increase in silage DM and a decrease in volatile fatty acids. Silage additives are, importantly, utilized to improve the nutritional value of the ensiled material at low cost, thus producing good quality silage for ruminant consumption. Therefore, HMPBs of adequate nutritional value can be used as silage additives.

5. Silage Additives on the Fermentation Characteristics and Aerobic Stability of HMBP Silage

To enhance the fermentation of ensiled materials, various additives such as chemicals (e.g., formic acid, sorbic acid, etc.) and microbial additives (e.g., LAB inoculants and enzymes) are added during ensiling.

5.1. Chemical Additives

Chemical additives 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 [49]. Ensiling citrus peels with either urea or sorbic acid reduced ethanol production and DM losses, and improved silage fermentation compared to the untreated silage [21]. Formic acid, one of the widely used chemical additives in the ensiling of HMPBs, is nowadays being substituted by organic additives. The interest of formic acid in silage fermentation is derived from its immediate lowering pH and its conservation attributes [50]. Researchers [51] ensiled wheat bran grain treated with formic acid or a combination of formic acid and propionic acid, which increased acetic acid and DM losses and improved the aerobic stability of the silage compared to the untreated silage. In contrast, others [19] reported a reduced silage pH when formic acid (3.5 L/t) was added to tomato pulp at ensiling. The addition of Kem (a mixture of formic acid, propionic acid, ammonium formate, and benzoic acid) to sugar beet pulp at ensiling increased lactic acid and reduced acetic acid and ethanol compared to the untreated silage [52]. The researchers also reported increased crude protein and nitrogen-free extract with additions of urea and formic acid, respectively, in sweet beet pulp during ensiling. Others [53] reported restricted fermentation and increased gas production but no influence on the aerobic stability of citrus pulp silage with the addition of urea.

It is apparent from Table 2 that the aerobic stability of silage from HMPBs was improved with chemical additives. Some researchers reported improved aerobic stability of sweet beet pulp silage with chemical additives compared to untreated silage [54–56].

However, chemical additives were reported to restrict the fermentation process in SBP silage [57]. They further indicated that higher doses of chemical additives increased the retention of the hardness of the sweet beet pulp silage. Researchers [58] treated apple pomace with urea or benal (contains sodium montmorillonite) and reported increased crude protein content in the silage. Consistently, adding urea to grape pomace increased the crude protein but reduced the IVDMD of the silage [59]. Ensiling tomato pulp with either grass hay or corn treated with alkali increased silage pH and decreased the in vitro organic matter digestibility (IVOMD) due to energy and crude protein losses in the silage compared to the untreated silage [60]. Sugarcane bagasse is a by-product of the sugar industry after juice extraction, and approximately 300 kg of sugarcane bagasse is produced from 1 ton of raw sugarcane [61]. Ensiling of sugarcane bagasse treated with alkali reduced silage pH and neutral detergent fiber, but improved silage aerobic stability and digestibility of DM and organic matter, as well as N retention, compared to the untreated silage [62].

Treatment of apple pomace silage mixed with either pear pomace or corn with a chemical additive did not affect either the fermentation or the aerobic stability of the silages. A researcher [63] compared silage from apple pomace mixed with pear pomace with silage from apple pomace mixed with corn. Treating this silage with a chemical additive did not influence either the fermentation or the aerobic stability of the silage compared to the untreated silage. Chemical additives can be used during the ensiling of HMBPs, but the challenge is their corrosiveness to implements and sometimes dangerous to handle.

Table 2. Effects of chemical or feed additives on the fermentation and aerobic stability of silages from high-moisture by-products.

By-Products	Chemical/Feed	Response		Reference
		Fermentation	Aerobic Stability	
Sugar beet pulp	Kem	Increased LA, reduced AA and ethanol	ND	[52]
Sugar beet pulp	Sodium formate/formic acid	Increased NFE	Improved	[64]
Sugar beet pulp	Konsil	Restricted	Improved	[55]
Sugar beet pulp	Formalin, sodium, and propionic acid	Restricted	Improved	[57]
Sugar beet pulp	Corn steep liquor	Increased effluent production	ND	[48]
Citrus pulp	Sorbic acid	Reduced silage DM losses, improved silage fermentation, and reduced ethanol production	ND	[21]
Citrus pulp	Urea	Increased ammonia-N and gas production	NS	[21]
Citrus pulp	Urea	Restricted	ND	[30]
Tomato pomace	Alkali	Increased pH	ND	[60]
Tomato pomace	Formic acid	Improved silage fermentation	ND	[19]
Brewer's grain	Formic acid	Increased AA and DM losses	ND	[51]
Sugarcane bagasse	Alkali	Reduced pH	Improved	[62]
Banana waste	Urea	Increased pH, VFA, and NH_3-N	Impaired	[34]
Grape pomace	Urea	Reduced IVOMD	ND	[59]

AA = acetic acid; DM = dry matter; IVOMD = in vitro organic matter digestibility; LA = lactic acid; NFE = nitrogen-free extracts; ND = not detected; NH_3-N = ammonia-nitrogen; NS = not significant; VFA = volatile fatty acid.

5.2. Microbial Inoculants

Microbial inoculants are products that contain either single or multiple strains of lactic acid bacteria and enzymes that are used to influence the fermentation of ensiled forages [10]. They are natural or manufactured products that are applied onto the forage at ensiling in liquid/powder or solid form to ensure that enough lactic acid bacteria are present on the forage to reduce storage losses, enhance rapid fermentation, improve the nutrient composition of silage, limit the extent of fermentation to reduce fermentation losses, and to improve bunk life of silage (increase aerobic stability) [10]. The author indicated that there are several silage inoculants that are available on the market with an inoculation rate that ranges between 10^4 and 10^6 colony-forming units (CFU)/g of fresh matter. Most commercially available inoculants contain homofermentative lactic acid bacteria that are fast and efficient producers of lactic acid and thus improve silage fermentation. However, these inoculants are mostly designed/produced to be used in the ensiling of forages to ensure enough lactic acid bacteria inoculation at ensiling. The response of various HMPBs to microbial inoculation at ensiling is presented in Table 3. Accordingly, microbial inoculation to HMPBs at ensiling has undergone the same pattern as with the forages, whereby some studies reported positive effects on silage fermentation dynamics while others reported a lack of response with microbial inoculation [65]. Researchers [66] reported reduced lactic acid production and aerobic stability in citrus pulp silage with propionic acid-producing bacteria. Inoculation of lactic acid bacteria to wheat bran grain did not affect the nutrient content but reduced the ammonia-N, yeasts, and mold concentrations and the pH, but increased the concentrations of lactic acid, acetic acid, and butyric acid of the silage [35,67]. The increase in lactic acid concentration in the lactic acid bacteria-treated silage was due to the amylolytic effect of certain microbes in the product, which attacked the starch and increased lactic acid. Ensiling yacon residue mixed with sweet beet pulp and treated with lactic acid bacteria inoculant reduced silage pH and ammonia-N and increased IVDMD compared to the untreated silage [44]. Others [68] ensiled citrus pulp mixed with wheat straw and treated with exogenous enzymes (anaerobic bacteria plus cellulase, xylanase, α-amylase, and protease) and reported increased crude protein, ether extract, and metabolizable energy, but reduced total phenolics, saponins, and alkaloids. The enzyme increased lactic acid, ethanol, and ruminal volatile fatty acids due to fiber hydrolysis and rumen fermentation activity but did not affect the degradation rates of DM and crude protein in the silage. Similarly, others [68] ensiled citrus pulp mixed with wheat straw and treated with microbial inoculants (i.e., LAB and enzymes). They reported improved metabolizable energy, organic matter digestibility, microbial protein, and the effective degradability of DM compared to untreated silage.

Mulberry (*Morus*) pomace, a by-product of the production of mulberry juice, which consists mainly of peels and stems, contains 156 g WSC/kg DM and accounts for approximately 8% of the fresh weight of the mulberry [25]. These authors inoculated the pomace with lactic acid bacteria at ensiling and reported reduced silage pH and increased lactic acid and gas production compared to untreated silage.

Some researchers [69] evaluated a fungus (*Rhizopus oryzae*) on the fermentation of potato (*Solanum tubersum*) wastes and reported a rapidly reduced pH and hardness of potato waste, which subsequently increased lactic acid concentration with the fungus. However, others [70] did not report benefits of lactic acid bacteria inoculation to potato waste. In contrast, inoculation to potato waste increased acetic acid concentration and improved aerobic stability but did not affect the DM and organic matter digestibility of the silage [71]. Further, researchers [10] ensiled a totally mixed ration that contained 80% potato waste treated with lactic acid bacteria inoculants and reported improved aerobic stability of silage as indicated by lower carbon dioxide production and low levels of yeast and molds compared to the untreated totally mixed ration silage. When feeding totally mixed ration silages to lambs, the lactic acid bacteria-inoculated totally mixed ration silage had higher feed intake, average daily gains, nutrient digestibility, and N retention compared to the other treatments. In another study, researchers [72] ensiled potato waste with microbial additives (i.e., lactic acid bacteria and enzymes) and reported reduced fiber fractions and increased, improved nutrient digestion and N retention in rams compared to the untreated silage. Consistently, others [15] added enzymes to potato waste at ensiling and reported reduced pH and fiber fractions but increased residual sugars, which subsequently reduced silage aerobic stability. Mixing potato waste with corn stalks and inoculating with microbial additives (i.e., lactic acid bacteria or enzymes) resulted in an enhanced lignocellulolytic degradation and preserved more fermentable carbohydrates compared to untreated silage [73].

Ensiling sugarcane bagasse mixed with corn stalks and inoculated with enzymes improved the degradation of DM and fiber fractions, improved nutrient digestibility, average daily gain, feed intake, and feed efficiency in goats [74]. However, high level of enzyme (3 mL/kg DM feed) addition decreased methane production in the sugarcane bagasse silage [75]. Inoculation of lactic acid bacteria plus molasses to sugarcane bagasse at ensiling increased the volatile fatty acids, milk yield, and total solids and reduced methane and somatic cell counts in dairy cows compared to untreated silage [76].

Some researchers [14] ensiled cassava (*Manihot esculanta Crantz*) pulp with microbial additives (i.e., lactic acid bacteria and enzymes) and reported an improved silage fermentation, increased crude protein, and reduction in neutral detergent fiber in the silage compared to the untreated silage. The treatments improved IVDMD and fiber digestibility. Silage microbial additives can be used during the ensiling of HMPBs, as is done with forages (e.g., grasses, cereal grains, and legumes), and the same effects as with forages can be expected from the ensiled HMPBs.

Table 3. Effects of microbial inoculation on fermentation characteristics and aerobic stability of silage from high-moisture by-products.

By-Products	Microbial Type	Response			Reference
		Fermentation	**Nutrients**	**Aerobic Stability**	
Citrus	Enzyme (ZADO®: Mixture of cellulase, xylanase, α-amylase, and protease).	Increased LA and ethanol	Improved CP + ME	ND	[8]
Citrus	LAB + enzyme (Lalsil: *Lactobacillus plantarum* and *Propionibacterium acidipropionici* + Natuzyme Plus: mixture of cellulase, xylanase, β-qlucanase, α-amylase, pectinase, phytase, proteases, and lipase).	Increased LA and reduced pH	Improved ME + OMD	ND	[68]
Citrus	LAB (Propionic acid-producing bacteria).	Reduced LA	ND	Poor	[66]
Brewer's grain	LAB (Mixture of *Lactobacillus plantarum*, *Enterococcus faecium*, and *Pediococcus pentosaceus* and fermentation extract from *Aspergillus oryzae*, *Trichoderma longibrachiatum*, and *Bacillus subtilis*.	Increased LA and AA, reduced pH, BA and NH$_3$-N	NS	ND	[67]
Yakon	LAB (Lactobacillus plantarum).	Reduced pH and NH$_3$-N	Increased ruminal methane	ND	[44]
Sugar beet pulp	LAB (Maize All: mixture of *Lactobacillus plantarum*, *Pediococcus acidilactic*, and *Lactobacillus salivarius* + α-amylase. Sil All: mixture of *Enterococcus faecuim*, *Pediococcus acidilactic*, and *Lactobacillus salivarius* + of cellulase, hemicellulose, Pentosanase, and amylase).	Improved	Reduced in vitro gas production	ND	[24]
Sugar beet pulp	LAB (Lalsil fresh: *Lactobacillus plantarum*).	Reduced pH and NH$_3$-N, increased LA	Reduced fiber IVDMD improved	ND	[31]
Sugar cane bagasse	Enzyme (Cellulase).	Increased LA and reduced pH	Increased degradation of DM and fiber	ND	[73]

Table 3. *Cont.*

By-Products	Microbial Type	Fermentation	Response Nutrients	Aerobic Stability	Reference
Mulberry pomace	LAB (Mixture of *Lactobacillus plantarum* and *Streptococcus*).	Reduced pH and increased LA	Increased gas production	ND	[25]
Potato pulp	LAB (Lalsil fresh: *Lactobacillus buchneri* and *Bonsilage forte*: *Lactobacillus paracasei*, *Lactobacillus lactis*, *Pediococcus acidilactici*).	Increased AA	Digestibility not affected	Improved	[71]
Potato pulp	LAB/enzyme (Novozyme: fibrolytic enzyme containing cellulose from *Trichoderma reesei*).	Reduced pH and increased LA	Reduced fiber	Impaired	[72]
Potato pulp	LAB (Silosolve: *Lactobacillus plantarum*, *Enterococcus faecium* and *Lactobacillus buchneri*).	Reduced pH and increased LA	Improved DM and CP degradability	ND	[77]
Avocado pulp	LAB/enzyme (Emsilage: *Lactobacillus plantarum*, *Enterococcus faecium* and *Lactobacillus buchneri*. Sil-All: *Lactobacillus plantarum*, *Pediococcus acidilactici*, *Pendiococcus pentosaceus*, and *Propionibacterium acidipropionici*).	Increased LA and pH not affected	Reduced fiber and DM, improved degradability	Impaired	[23]
Grape pomace	LAB (*Lactobacillus plantarum*).	Reduced pH and increased LA	-	Improved	[78]
Grape pomace	LAB (*Lactobacillus plantarum* and *Lactobacillus buchneri*).	Reduced pH and polyphenol	Reduced fiber	Improved	[46]

AA = acetic acid; NH_3-N = ammonium nitrogen; BA = butyric acid; CP = crude protein; IVDMD = in vitro dry matter; LA = lactic acid; LAB = lactic acid bacteria; ME = metabolizable energy; ND = not detected; NS = not significant; OMD = organic matter digestibility.

6. Effects of Dietary Addition of Silages from HMPBs on Animal Growth Performance and Products

It has been well-documented that the substitution of a concentrated diet with silages from HMPBs can successfully reduce the cost of feed. Some of the conventional feed ingredients may not be available or affordable to the farmers, hence using silage from HMPBs may be a good option. The response of animals to the dietary addition of silage from HMPBs varies (Table 4), mainly due to different nutrient compositions of the silages.

Feeding dairy cows with a diet containing 30 kg of sweet beet pulp silage resulted in increased milk yield compared to a diet containing 20 kg of corn silage [79]. In contrast, others [80] replaced either corn silage or cob corn silage with sweet beet pulp silage in the diet of dairy cows and reported reduced dry matter intake with no effects on milk yield and content. However, they reported improved digestibility of organic matter 9and the metabolizable energy concentration in sheep fed diets containing sweet beet pulp silage. They concluded that sweet beet pulp silage has specific effects on ruminal fermentation that may depress feed intake in cows but improved digestibility and recommended a 20 kg inclusion level in the ration of dairy cows. The supplementation of either barley or soybean meal to sweet beet pulp silage improved the growth rate of beef cattle compared to those fed either on grass silage or concentrate-based diets [81].

A study [82] reported no significant difference in the growth performance of lambs fed citrus pulp silage mixed with wheat straw in comparison with those on the commercial diet. However, the carcasses of lambs had better muscular conformation and reduced fat content than those fed on the commercial diet. In addition, others [8] added citrus pulp silage to a basal diet and reported improved ruminal fermentation in lambs due to improvement in the activity of ruminal microbes, which led to improved feed efficiency and live weight gains in lambs compared to the basal diet. However, the substitution of tropical grass hay with either pineapple (*Ananas comosus*) pulp silage or citrus pulp silage at 20% was inadequate to affect the digestibility of DM and crude protein in rams [22].

A study [83] compared apple pomace silage (produced with wheat straw) with corn silage on the in-situ degradability in wethers. The effective degradability of DM and that of crude protein were reduced with apple pomace silage compared to corn silage due to the presence of wheat straw in apple pomace silage. One of the challenges of ensiling apple pomace is the increase in alcohol (189.1 g/kg DM) production, which restricts the use of silage in ruminants' diets [84]. Adding 20% apple pomace in a totally mixed ration at ensiling increased ethanol production but reduced N retention and nutrient digestibility in wethers [85]. The researchers recommended that apple pomace should not exceed 20% of the dietary DM. This is because the high number of soluble sugars in apple pomace can be fermented in the rumen, causing alcoholaemia, which intoxicates the animals [23]. Others [86] reported that ewes can take up to 15.1 g/d of ethanol from AP silage without adverse side effects. They recommended that this silage should be fed to ewes with hay cubes or dry roughage, up to 50% of the total diet.

A study [87] replaced alfalfa hay with up to 30% dietary inclusion levels of tomato pulp and apple pomace mixture silage for dairy cows. The silage reduced chewing activities, improved the digestibility of DM and organic matter, increased blood metabolite concentration, and increased the ruminal concentration of acetic and propionic acids compared to a diet with no silage. Using the same silage (i.e., tomato pulp and apple pomace AP mixtures), researchers [88] replaced berseem hay in a concentrate diet of goats and reported that the 50% replacement of berseem hay with pomace silage resulted in better nutrient digestibility and feeding value compared to the control. This silage improved milk yield, milk fat, and average daily gain in goats compared to the control. Others [89] ensiled tomato pulp mixed with wheat straw and compared the silage with alfalfa hay in terms of nutrient digestibility in sheep. The tomato pulp silage produced with 10% wheat straw was comparable to alfalfa hay in terms of nutrient digestibility in sheep. Some researchers [20] ensiled tomato pulp with 20% corn grains, and the feed intake of the silage by ungulate animal species was higher than those fed on corn silage alone.

According to some researchers [90], pear pomace silage has an IVOMD of 72% and an ME of 10.7 MJ/kg DM, making it a good feed resource. These authors compared the dietary replacement of corn silage with up to 62% pear pomace silage and reported no effect on the growth performance and nutrient digestibility in sheep. However, feeding a totally mixed ration that contained the pear pomace silage to dairy cows resulted in increased milk yield and milk fat composition compared to cows fed on a totally mixed ration that contained Napier grass. In another study, the substitution of Napier grass with pear pomace silage increased the in-situ disappearance of DM and crude protein and increased the effective degradability of DM and fiber fractions [91]. In addition, some researchers [92] reported increased hot and cold carcass yields in lambs fed pear pomace silage compared to those fed Napier grass. Further, the substitution of pangola (*Digitaria eriantha*) hay with pear pomace silage in the diets of Thai cattle resulted in increased digestibility of nutrients with the silage than the grass hay [93]. Adding 25% of pear pomace silage to the basal diet of cattle resulted in higher intakes of DM and crude protein and improved energy balance, which resulted in improved average daily gain and body weight gain compared to cattle fed diets containing Napier grass [78].

A study [94] produced grape pomace silage, which was used to replace corn silage in the diets of lambs and reported reduced dry matter intake and average daily gain in lambs with increasing grape pomace silage in the diet. However, total phenolics and copper concentration in the liver were increased, while carcass fat was reduced with grape pomace silage.

It should be noted that the potato waste silage has a gross energy of 19.5 MJ/kg DM, which is comparable to 20 MJ/kg DM in corn silage, with IVDMD of 75.5% in potato waste silage compared to 68.3% in corn silage [95]. These researchers substituted rolled corn with potato waste silage in grass-based diets for steers and reported no effect on ruminal N utilization, ruminal pH, or volatile fatty acids concentration. However, the ammonia-N in the rumen fluid, ether extract intake, and post-ruminal digestibility were reduced in steers fed the potato waste silage. The high energy digestibility of potato waste silage is reported to be closely associated with the high starch content of the by-product, which can be slowly degraded by rumen micro-organisms than starch from wheat [96]. Others [97] ensiled potato waste mixed with corn straw and reported an increased ruminal ammonia-N but did not affect the growth performance of beef cattle. A study [77] produced potato waste silage that was inoculated with lactic acid bacteria and reported improved dry matter intake with lactic acid bacteria, but the digestibility was not affected. The improved animal performance from silage inoculated with lactic acid bacteria might be because 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 in the silo during ensiling of forages [6]. This is one of the reasons for improved growth performance and production in ruminants fed microbial-treated silages compared to those fed untreated silage.

Fiber fractions in potato waste silage were not affected by microbial inoculation, but the rumen degradation of dry matter, crude protein, and fiber fractions was improved compared to untreated silage [98]. Researchers [99] ensiled potato waste with either pelleted sweet beet pulp or wheat bran and reported improved digestibility of dry matter and organic matter in steers fed potato waste silage produced with pelleted sweet beet pulp than wheat bran. Supplementation of 15% potato waste silage to a basal diet of dairy cows increased the vaccenic acid and conjugated linoleic acid in milk compared to cows supplemented with barley [100]. Substitution of a concentrated diet with 300 g/kg DM of potato waste silage can be fed to fattening Mehraban lambs without adverse effects on animal performance [101].

Silage produced from spearmint (*Mentha spicata*) by-products was reported to contain low digestible energy; hence, it was poorly utilized by steers due to its high acid detergent lignin content compared to barley silage [102]. Ensiling of carnation (*Dianthus caryophyllus*) by-product (227 g/kg DM) was reported to reduce the crude protein content while increasing the fibrous fractions of the by-product [103]. However, the dry matter intake of the silage was improved compared to feeding the by-product in fresh form to goats. A study [104] produced silage from jackfruit (*Artocarpus heterophyllus*) residue and replaced 50% of finger millet straw in the diet of sheep. They reported improved average daily gain in sheep fed diet containing the silage, but the dry matter intake and nutrient digestion were not affected. Well-preserved silages from HMBPs can be incorporated into a diet or fed to livestock without imposing negative impacts on the animals. This will help to reduce environmental pollution, since these HMBPs will be fed to animals at low cost.

Table 4. Effect of partial replacement of basal diet with silage from high-moisture by-products on animal performance and products.

By-Product	Inclusion Rate	Animal Response			Reference
		Animal	Growth Performance	Milk/Carcass	
Spearmint	-	Steers	Poor	ND	[101]
Carnation	-	Goats	Improved DMI	ND	[102]
Sugar beet	-	Cows	Reduced DMI	ND	[79]
Sugar beet	20%	Sheep	Improved OMD	NS	[79]
Potato waste	15%	Cows	NS	Increased milk vaccenic acid and conjugated linoleic acid	[99]
Pineapple pulp	20%	Sheep	Performance unaffected	ND	[22]

Table 4. *Cont.*

By-Product	Inclusion Rate	Animal Response			Reference
		Animal	Growth Performance	Milk/Carcass	
Pine apple pulp	-	Sheep	Improved in situ disappearance of DM and CP	Improved degradability	[90]
Pineapple pulp	-	Sheep	Improved nutrient digestibility	Improved warm and cold carcass yield	[91]
Pineapple pulp	25%	Cattle	Improved DM, CP, and ADG intake	ND	[77]
Pineapple pulp	62%	Cows	Improved nutrient intake	Increased milk yield and composition	[89]
Tomato pomace	Alfalfa hay	Sheep	Reduced OM and CP digestibility	ND	[88]
Tomato pomace	50% Berseen hay	Goats	Improved nutrient digestibility	Improved milk yield and milk fat content	[87]
Tomato pomace + Apple pomace	30%	Cows	Improved OM and DM digestibility	ND	[86]
Tomato pomace	-	Cows	Nutrient digestibility unaffected	Milk production and composition unaffected	[105]
Tomato pomace	Alfalfa hay	Sheep	Reduced OM and CP digestibility	ND	[88]
Apple pomace	-	Sheep	Reduced DM and CP degradability	ND	[82]
Grape pomace	-	Sheep	Reduced DMI and weight gains	Reduced carcass fat	[93]
Citrus	-	Sheep	NS	Reduced carcass fat content	[81]
Citrus	-	Heifers	Improved LWG and FE	ND	[8]
Brewer's grains	-	Heifers	Improved FE	ND	[28]

ADG = average daily gain; CP = crude protein; DM = dry matter; DMI = dry matter intake; FE = feed efficiency; LWG = live weight gain; ND = not detected; NS = not significant; OM = organic matter; OMD = organic matter digestibility.

7. Conclusions

Good-quality silage can be produced from HMPBs, provided all principles of ensiling are followed. The most underpinning challenge related to this silage is its poor aerobic stability due to increased residual sugars, which can be corrected by using chemical and microbial additives, especially those that increase the production of acetic acids. If well-produced, the silage can partially substitute the basal diet of ruminants without adversely affecting animal performance.

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