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SAMMENDRAG/SUMMARY:

Sammendrag: Ensilering er en vanlig konserveringsmåte for dyrefôr. I denne prosessen gjennomgår fôret melkesyregjæring i et anaerobt miljø som senker pH og hindrer uønsket nedbryting av næringsstoffer. Vanlige silotyper inkluderer topplastede tårnsiloer, sidelastede plansiloer, nedgravde siloer og gropesiloer samt innplastede rundballer og pølser. Silotype er flere ganger vist å påvirke surfôrets egenskaper og næringsverdi, men graden av påvirkning er også avhengig av materialet som blir ensilert. Densitet er en annen faktor som påvirker næringsverdien og tap fra surfôr. Vanligvis resulterer høy densitet i mindre tap av biomasse enn lav densitet, men andre egenskaper i det ensilerte materialet kan påvirke effekten av densiteten. Formålet med denne litteraturstudien var å identifisere faktorer som kan modifisere effektene av i) surfôrdensitet og ii) silotype på tap av biomasse, gjæringsmønster, næringsverdi og kontaminering av mykotoksiner. Et systematisk søk ble gjort i databaseplattformen Web of Science core collection. De fleste studiene viste en positiv korrelasjon mellom surfôrdensitet, gjæringskvalitet og næringsverdi, og negativ korrelasjon mellom densitet og biomassetap. Disse studiene var imidlertid hovedsakelig gjennomført på laboratorium. I tillegg varierte effektene av densitet og silotype mye mellom studier. Videre undersøkelser av densitetseffekter på gjæring og næringsverdi under praksislike forhold kunne gi mer informasjon om disse effektene på ulike skalaer. Sammenligningene av silotyper indikerer at rundballer, bags og pølser kan være gunstigere for surfôrkvalitet og biomassebevaring enn plansilo. Ingen av studiene som kom fram i litteratursøket hadde sett på hvordan silotype påvirket tap og kvalitet på maisensilasje som er en av de vanligste fôrtypene.

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Preface

This report presents the results from a literature review that was conducted by NIBIO as part of the project “Fremtidens fôrsystem – Industri 5.0 for en bærekraftig agri-industri”.

It is an innovation project for the industrial sector (IPN) and is financed by Orkel AS and TKS Agri AS with support from The Research Council of Norway.

The design of the review and search strings were discussed with Orkel AS in beforehand.

The authors alone are responsible for the interpretation of the results.

Særheim, 22.04.24

Tomas Persson

English Summary

Ensiling is a common mode of preservation of animal feed. In this process, the feed undergoes lactic acid fermentation in an anaerobic environment, which decreases pH and inhibits degradation of the feed and its nutritive value. Common silos include top loaded tower silos, side loaded bunker silos (also called horizontal silos), underground pit and trench silos, and bales and tubes wrapped in plastic film. Previous studies have revealed that the type of silo often have an impact on silage properties and feed value, but these effects can vary between silage materials. Silage density is another key factor for silage nutritive value and losses. Generally, high density results in smaller losses than low density, both in bunker silos and bales, but the density effect can also be influenced by properties of the ensiled material. The objectives of this literature review were to identify factors and conditions that can modify the effect of i) silage density, and ii) silo type on dry matter losses, leaching of nutrients, fermentation characteristics, silage feed value and mycotoxins contamination. A systematic literature search was carried out in in the Web of Science core collection platform of databases. Most studies showed positive correlations between silage density, and fermentation and feed value, and negative correlations with DM losses. The majority of these studies were conducted at laboratory scale and there was also a great variation in the magnitude of these effects. Further investigations at farm scale may provide more information about the consistency of these effects across experimental scales. The silo type comparisons indicate that silage bales, bags and tubes can be favourable for silage quality and dry matter preservation compared to bunker silos, but information on silo type effects on important crops such as maize is missing.

Content

1 Introduction

Animal feed has been preserved as silage since the 1940ies (Bernardes et al., 2018). The preservation is based on lactic acid fermentation in an anaerobic environment, which decreases the pH and inhibits degradation of the feed and its nutritive values (da Silva et al., 2017). The rate and direction of the fermentation processes and its effect on the quantity and quality of the animal feed are affected by several factors. These factors include the physical and chemical properties of the plant material to be harvested and ensiled (Bernardes et al., 2018; Borreani et al., 2018). The environmental conditions during the period from cutting to sealing as well as physical, chemical and biological processes within the sealed container are likewise of high importance to the silage quantity and quality (Borreani et al., 2018).

The properties of the plant material before and at start of the ensiling process are related to plant species, developmental stage and cutting management such as cutting height, shredding and chopping, and wilting in the field (Macedo et al., 2019). Field drying and dry matter content can also have a major impact on field losses. For maize, within the range of 25-39 % dry matter, wetter material resulted in less losses than drier material (Borreani et al., 2018). Wilting also normally increases the quality of round bale silage (Bernardes et al., 2018). Conditioning by steel flails and tedding reduce wilting time but may also reduce crude protein content in legumes (Borreani et al., 2018). Chopping can also increase the quality of round bale silage (Bernardes et al., 2018). In tropical and subtropical regions, quantity losses can be exacerbated by warm and wet conditions before and during harvest as well as high ensiling temperatures (Borreani et al., 2018). Temperature also affects the growth rate of lactic acid bacteria (Borreani et al., 2018).

Common silos include top loaded tower silos, side loaded bunker silos (also called horizontal silos) (Savoie and Jofriet, 2003), underground pit and trench silos (Gebrehanna et al., 2014) and bales and tubes wrapped in plastic film (Coblentz and Akins, 2018). Sealing of the silo is crucial to favorable fermentation conditions. Oxygen in pores in the forage before the start of the fermentation during the first period after sealing is removed mainly by respiratory processes in the plant tissue. Such aerobic reactions consume nutrients and energy leading to quantitative and qualitative losses (Borreani et al., 2018), and aerobic microorganisms are considered the most important factor that causes losses in silage making (Bernardes et al., 2018). Accordingly, delayed sealing of forage maize by up to 4 days has been shown to result in considerable quantity losses as well as unfavorable quality changes (Brüning et al., 2018). As for round bales, a positive relationship between the number of layers of plastic film wrappings and silage quality have been reported (Hancock and Collins, 2006). Also the type of plastic wrapping can have an impact on the chemical composition of the silage (Saijpaul et al., 2013) as can the type of bunker silage covering (Lima et al., 2017).

The density of silage can have a great impact on its nutritive quality as well as on dry matter losses. Oxygen movement within silage depends on its porosity, which, in turn, is related to the silage density, but also to dry matter and organic matter contents (Borreani et al., 2018). Generally, high density results in smaller losses than low density, both in bunker silos and bales (Bernardes et al., 2018). This negative relationship between density and losses is usually stronger for maize than for grass silage (Borreani et al., 2018). In bunker silos, the packing density is usually much lower in peripheric layers than in central layers (Bernardes et al., 2018) mostly due to self-packing in latter (Muck and Holmes, 2000), which risks causing uneven quality. The packing density of round bales is largely an effect of the chamber pressure within the baler (Borowski et al., 2021). Also the method of unloading bunker silos can, to some extent, affect the silage characteristics and feed value (Muck and Huhnke, 1995).

Additives, including organic acids, salts and inoculated bacteria, are commonly used to increase silage aerobic stability, i.e. the ability to withstand deterioration under aerobic conditions (Wilkinson and Davies, 2013), by reducing pH, increasing lactic acid content, and decreasing compounds which are detrimental to silage fermentation and quality (Duniere et al., 2013; Muck et al., 2018; Carvalho et al., 2021). Also undesired contaminants, notably fungi that produce mycotoxins, can have a large negative impact on the nutritive value of the ensiled feed (Wambacq et al., 2016; Ogunade et al., 2018). Mycotoxins in silage may originate from both pre- and post-harvest fungal contamination, and the environmental and physiological conditions that favour mycotoxin production vary widely between fungal species and mycotoxins (Ogunade et al., 2018).

Numerous experimental studies and farm surveys have been published about the effect of silage density, type of silo, additives and contaminants, on silage quantitative yield, and its feed value. The impact of the weather, plant structure and composition and pre-ensiling treatments has also been extensively studied for a wide range of crops. A review studies in these fields could help identify and interpret interaction effects of these factors on feed value and losses. Such identifications could, in turn, help design and adjust silage making systems to better meet animal feed requirements and keep the production costs lower.

The objectives of this review were to identify factors and conditions that can modify the effect of

i) silage density
ii) silo type

on dry matter losses, fermentation characteristics, leaching of nutrients and silage feed value and mycotoxins contamination. The modifying factors were i) plant material (species (mixtures), developmental stage at cutting) ii) type of pre-ensiling treatment and dry matter content before ensiling, and iii) the use of additives.

2 Review structure

This review considered articles about silage making from whole crop maize, perennial grasses and legumes such as lucerne (alfalfa) and clover, and mixtures of perennial grasses and legumes. Silage of other crops or by-products from other types of plant material processing was not included. The following combination of words were searched for in the Web of Science core collection platform of databases: *silage AND compacting, silage AND compactness, silage AND packing, silage AND packing AND round bales, silage AND aerobic stability AND losses, silage AND aerobic stability AND packing, silage AND aerobic stability AND density, round bales AND density, silage AND loss AND bales, silage AND loss AND bunker silo, silage AND additives AND density, silage AND additives AND compaction, silage AND bunker silo AND round bales, silage AND loss AND bale**, *silage AND mycotoxin* AND bunker silo,* silage *AND mycotoxin* AND bale*, silage AND density AND loss, silage AND density AND nutritive value.* References which did not included the crops listed above were removed and not considered further.

3 Effect of silage compaction/density

There were quite a few studies that showed a relationship between compaction pressure and silage density across a range of conditions. However, this relationship varied between studies with different silage making treatments and crops (Table 1). A great number of studies have examined the effect of silage compaction or density on fermentation characteristics, dry matter loss or feed value for different crop, silos and other technical factors. Besides, silage density has often been reported in studies where it was not included as an experimental factor, which to some extent enables a comparison between studies.

Table 1. Effects of compression pressure on silage density

type of silo	crop	main findings	reference
laboratory silo	alfalfa, maize	Impact shredding resulted in 26 % to 56 % (alfalfa) or 9 % to 17 % (maize) greater density than chopping (and chopped and on-board kernel processor for maize)	(Pintens et al., 2023a, b)
bales	alfalfa	4 % higher density in bales with material that was chopped with a cutting system behind a windrow pickup of a chamber round baler than in unchopped material	(Borreani and Tabacco, 2006)
bales	alfalfa	Moisture content reduced, and baler feeding speed increased maximum compression pressure. A positive relationship between compaction pressure and silage density	(Fang et al., 2019)
mini silo	*Miscanthus*, *Spartina pectinata*, big bluestem grass	Greatest effect of compaction on density after the first cycles of compaction on the first layer of subsequently added horizontal plant material layers. (3 cycles of compaction per layer)	(Lisowski et al., 2020)
bags	pasture grass, maize	Grass silage deviated much more than maize silage from the tolerance range for plastic bag elongation, i.e. storage density was more easily controlled for maize than for grass silage. Density varied between 179.0 and 280.8 kg DM m^{-3} (maize), and 89.3 and 197.7 kg DM m^{-3} (grass)	(Mostafa et al., 2020)
haylage bales	Barenbrug BG-5 forage mix	Highest bale density at moisture content of 56 % and 1.8 MPa pressing pressure	(Borowski et al., 2021)

3.1 Effect on fermentation characteristics

Wang et al., (2022) found that, within a range of 300 to 700 kg/m^3, higher compaction density of maize, lowered silage fermentation temperature, and that the lactic acid content was highest at the high density (700 kg/m^3). Likewise, both Kung et al. (2021) and Jungbluth et al. (2017) found a positive effect of density on aerobic stability of maize in laboratory scale silos. However, an, on average, 4 % higher alfalfa bale density due to chopping did not have any effect on silage pH, lactic acid or butyric acid concentration (Borreani and Tabacco, 2006), which is in contrast to reports about a positive relationship between density and aerobic stability in alfalfa silage in different types of bunker and wedge silos on farms (Ruppel et al., 1995). Other studies of alfalfa silage showed that higher density in chopped, compacted and bagged silage was associated with lower pH, lower acetic acid content and higher initial lactic acid concentration than in unchopped baled silage (Nicholson et al., 1992) or positive effects of shredding on both density and fermentation characteristics including higher lactate concentration and lower pH, and NH_3 and butyric acid concentration (Samarasinghe et al., 2019). For *Brachiaria* grass, compaction densities between 550 and 650 kg m^{-3} in laboratory silos had no effect on aerobic stability (Saute et al., 2021). In other laboratory scale studies, Camargo do Amaral et al. (2007) found that higher marandugrass silage density was associated with low silage pH, Yunus et al. (2001) that pH and acetic acid and butyric acid concentration decreased, and lactic acid concentration increased with density of napiergrass silage, and Tavares et al. (2009) that pH and ammonia N concentration in Tanzania grass silage were lower at high than at low density. Results from laboratory studies of silages made from temperate forage grasses are a bit contradictory. Compaction of perennial ryegrass silage led to decreased pH and an increased number of lactic acid bacteria (McEniry et al., 2007) while Franco et al. (2022) found higher lactic acid concentration in a red clover, timothy grass and meadow fescue silage compacted to a density of 583 kg m^{-3} (202 kg DM m^{-3}) than in the same type of silage compacted to 424 kg m^{-3} (147 kg DM m^{-3}) but no difference in aerobic stability. In a density study of timothy grass dominated silage in a bunker silo, no effect on silage aerobic stability was found (Randby et al., 2020).

3.2 Effects on dry matter and effluent losses

Robinson et al. (2016) found that silage bulk density had no significant effect on shrink loss (i.e. loss of fresh chopped crop between ensiling and feedout) from maize in large scale wedge and bunker silos, whereas Griswold et al. (2010) and Ashbell and Weinberg (1992) showed that higher density decreased maize silage dry matter loss from bunker silos; in the latter study the density was increased by sheeting sand bag anchorage. Likewise, Muck and Holmes (2006) reported that DM losses were associated with lower density within the density range 160 to 270 kg DM m^{-3} in bagged alfalfa, maize and red clover silage in a farm research study, and Camargo do Amaral et al. (2007) reported that increased density of marandu (*Brachiaria*) grass silage was associated with reduced losses. Also DM losses of perennial ryegrass in bunker silos have been reported to be lower at higher densities than at lower densities (Williams et al., 1997). However, Saute et al. (2021) reported that effluent losses from *Brachiaria* grass silage were higher at densities of 650 and 600 kg m^{-3} than at a density of 550 kg m^{-3} at laboratory scale.

3.3 Effects on nutritive value

In maize silage, crude protein (CP) content in dry matter was higher at 700 kg m^{-3} than at 300 kg m^{-3} density and Acid Detergent Fibre (ADF) and Neutral Detergent Fibre (NDF) content were negatively correlated with density (Wang et al., 2022). Also, Kruger et al. (2020) found a negative correlation between density on the one hand and NDF, and ADF content on the other hand, while the silage starch content was positively correlated with density in maize silage sampled from bunker silos at farms. Moreover, Pintens et al. (2023 b) found higher CP content in silage at laboratory scale that had been processed by impact shredding to reach a higher density than in non-impact shredded material with a lower density but no effect of this treatment on ADF or NDF, whereas Bruning et al. (2018) found only small effects of silage density on crude ash, CP, crude fibre (CF), neutral detergent fibre (aNDFom), starch and non-protein nitrogen (NPN) in laboratory silos. Sucu et al. (2016) showed that high density in laboratory scaled silos had a positive impact of maize silage digestibility. Fewer comparisons of density effects on feed value were found for grass silage than for maize silage. In the study by Franco et al. (2022) there were no differences in ash, CP, ammonia N content or yeast, mould and clostridia between two compaction densities (see above) in cylindrical pilot scale silos with 12-L capacity, while Camargo do Amaral et al. (2007) showed lower NDF and ADF concentration and nitrogen bound in the NDF fraction (NIDN), and strongly bound B3 fraction nitrogen and higher in vitro digestibility in high density than in low density marandu (*Brachiaria*) grass silage in experimental silos. McEniry et al. (2007) showed that NDF and ADF concentrations were also lower in high density than in low density perennial ryegrass in experimental silos.

Table 2. Density effects on fermentation characteristics

density	type of silo	crop	main findings	comments	reference
300, 450, 600 and 700 kg m^{-3}	7.2 L laboratory silo	maize	A significant non-linear relationship between density and fermentation-accumulated temperature. The multiple linear regression model between the accumulated-fermentation temperature and nutrition loss was significant under different densities.		(Wang et al., 2022)
215 kg DM m^{-3} (chopped, no further processing); 230 kg DM m^{-3} (chopped + on board kernel processed) 250 kg DM m^{-3}; (impact shredded once) 268 kg DM m^{-3} (impact shredded twice)	laboratory silos	maize	Higher lactic acid and crude protein conc. and lower pH in high density impact shredded material than in on-board kernel processed and chopped material.	Impacted shredding 1 time or 2 times compared with chopped untreated and chopped and on-board kernel processed	(Pintens et al., 2023 b)
168 and 216 kg of DM m^{-3}	mini silos (1.5 L anaerobic jars, Weck, Germany)	maize	High density silage had lower acetate content, ammonium N conc., and fermentation losses than low density. No lactate difference between the two densities.		(Sucu et al., 2016)

density	type of silo	crop	main findings	comments	reference
chopped: 167-204 kg DM m^{-3}, unchopped: 163-196 kg DM m^{-3}	bales	alfalfa	On average 4 % higher density in chopped material than in unchopped material across three trials. No effect of chopping on fermentation (pH, lactic acid, butyric acid)	Chopping with a cutting system installed behind a windrow pickup behind a fixed chamber round baler	(Borreani and Tabacco, 2006)
High moisture content (MC) treatment: 207 and 175 kg DM m^{-3}. low MC treatment: 199 and 167 kg DM m^{-3}	bales (1.5 m in diameter and 1.2 m in length)	alfalfa	Higher bale density resulted in lower pH, and for the higher moisture content treatment, also in higher propionic acid concentration.	Moisture content 450 or 550 g kg^{-1}	(Han et al., 2004)
Not measured	small bags (chopped material) and bales (non chopped material)	predominantly alfalfa	Lower pH, higher acetic acid and initially higher lactic acid in chopped and compacted bag silage than in the bale silage. Higher acetic acid conc. in bags than in bales and also in wet silage. Higher protein degradation (measured as NH_3-N/total N ratio), yeast and clostridia counts and butyric acid in bales than in bags.		(Nicholson et al., 1992)
Not measured	bunker, wedge (different types)	alfalfa, grass	Compacting and higher density associated with improved aerobic stability	Farm scale study	(Ruppel et al., 1995)
Non shredded material: 124 –163 kg DM m^{-3}; Shredded material: 177 to 236 kg DM m^{-3}	laboratory-scale silos	lucerne (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), perennial ryegrass (*Lolium perenne* L.) and a grass-clover mixture	Shredding increased density and decreased silage weight loss, pH, NH_3 and butyrate conc, and increased lactate concentration		(Samarasinghe et al., 2019)

density	type of silo	crop	main findings	comments	reference
550, 600 and 650 kg m^{-3}	experimental PVC silo	*Brachiaria brizantha* cv. Paiaguas grass	No effect of particle size and compaction density on aerobic stability	theoretical particle sizes (TTP 5; 8 and 12mm)	(Saute et al., 2021)
High: (77g/100ml), medium: (63g/100ml) low (49g/100ml)	laboratory silos	napiergrass (*Pennisetum purpureum*)	pH value, acetic acid, butyric acid, volatile basic nitrogen/total nitrogen ratio decreased with higher density. Lactic acid increased with higher density. No N fertilizer effect other than on N content	Density effects determined in combination with two N fertilizer levels: 50 kg ha^{-1}, 0 kg ha^{-1}	(Yunus et al., 2001)
Compaction pressure in compacted treatment 11. 66 kPa (density not stated)	13.6 L laboratory pipe silos (height, 0·75 m; internal diameter, 0.152 m	perennial ryegrass	Lower pH and higher DM content in compacted than in uncompacted silage. Larger number of lactic acid bacteria in compacted unwilted than in compacted wilted silage. Generally dry-matter content of herbage and infiltration of air had a greater impact on silage conservation than compaction	Air infiltration effects also studied	(McEniry et al., 2007)
500 kg m^{-3} (136 kg DM m^{-3}) and 665 kg m^{-3} (179 kg DM m^{-3})	laboratory cylindrical silo (12 L)	red clover (dominated) and timothy grass	Compaction reduced silage fermentation.	Soil and faeces contamination also investigated which stimulated non-desired fermentation	(Franco et al., 2022)

Table 3. Density effects on dry matter losses and effluents

density	type of silo	crop	main findings	comments	reference
varying	large silage piles (4 wedge, 2 rollover/wedge, 1 bunker)	maize	Silage density had no effect on shrink loss (loss of fresh chopped crop between ensiling and feedout)		(Robinson et al., 2016)
varying	bunker silo	maize	Inverse relationship between DM loss and density		(Griswold et al., 2010)
not stated	bunker silo	maize	Higher density as an effect of sheeting sand bag anchorage resulted in lower DM losses		(Ashbell and Weinberg, 1992)
between 160 and 270 kg DM m^{-3}	bag silos	23 alfalfa, 1 red clover, 23 maize bags	DM losses related to high porosity in low density bags	Research farm study	(Muck and Holmes, 2006)
Low density: 163 - 182 kg DM m^{-3} across 3 trials; High density 167-190 kg DM m^{-3}	round bales	alfalfa	Highest dry matter losses from the high density bales at two moisture levels	The density difference was a result of material chopping (see Table 1)	(Borreani and Tabacco, 2006)
100, 120, 140 and 160 kg DM m^{-3}	experimental silos 7 L capacity	Marandu (*Brachiaria*) grass	Higher bulk density silos showed lower DM losses		(Camargo do Amaral et al., 2007)
Compaction pressure in compacted treatment 11. 66 kPa (density not stated)	13.6 L laboratory pipe silos (height, 0·75 m; internal diameter, 0.152 m	perennial ryegrass	Lower effluent production in compacted than in uncompacted silage	air infiltration effects also studied	(McEniry et al., 2007)
Surface pressure of 4.1 kPa in the compacted treatment. The other treatment included no such compaction pressuring	bunker silo	ryegrass	DM losses due to aerobic activity during 120-150 days storage 0.3 % (compacted) and 0.9 % (uncompacted).	Gaseous exchange mainly by permeation during fermentation and feed-out.	(Williams et al., 1997)
tractor compaction: 204 kg DM m^{-3}; wheel loader compaction: 222 kg DM m^{-3}	bunker silo	timothy dominated grass silage	Higher DM density after wheel loader compaction than tractor compaction. No effect of compaction method on weight and packing machine on DM losses, silage composition and aerobic stability		(Randby et al., 2020)

Table 4. Density effects on feed value

density	type of silo	crop	main findings	comments	reference
silage samples from farms with naturally varying density	bunker silage	maize	A negative correlation between density and NDF, and ADF on a DM basis. Starch positively correlated with density on a DM basis		(Kruger et al., 2020)
194 ± 4 kg DM m^{-3} or 234 ± 3 kg DM m^{-3}	120 L plastic silos	maize	Only small effects of compaction on DM and nutritive value (crude ash, CP, CF, aNDFom, starch and NPN) regardless of sealing treatment. Higher impact of delayed sealing than of compaction on silage quality	Effects of compaction, sealing 0, 2 and 4 days after cutting and aerobic exposure after ensiling on silage quality and formation of volatile organic compounds	(Brüning et al., 2018)
215 kg DM m^{-3} (chopped, no further processing); 230 kg DM m^{-3} (chopped + on board kernel processed) 250 kg DM m^{-3}; (impact shredded once) 268 kg DM m^{-3} (impact shredded twice)	laboratory silos	maize	No effect on shredding/density on NDF and starch concentration	Impacted shredding 1 time or 2 times compared with chopped untreated and chopped and on board kernel processed	(Pintens et al., 2023 b)
168 and 216 kg of DM m^{-3}	mini silos (1.5 L anaerobic jars, Weck, Germany)	maize	High density higher digestibility than low density		(Sucu et al., 2016)
varying with compacting technique	experimental silos	maize, maize and red clover, maize and fodder goat's rue	The compacted maize and fodder goat's rue (3:1), and red clover and maize mixtures (1:1) had lower pH and higher organic matter digestibility than the compacted maize and fodder goat's rue (1:1) mixture	compaction by centrifugal direct-action vibrators	(Jasinskas et al., 2012)

density	type of silo	crop	main findings	comments	reference
not measured	small bags (chopped material) and bales (non chopped material)	predominantly alfalfa	Digestibility of the ADF fraction was higher ($P < 0.05$) for bale than for bag silages.		(Nicholson et al., 1992)
550, 600 and 650 kg m^{-3}	experimental PVC silo	*Brachiaria brizantha* cv. Paiaguas grass	The highest volume of effluent was found in silages with higher compaction densities (600 and 650 kg m^{-3}) and lower particle size (5 vs. 8 mm).	theoretical particle sizes (TTP 5; 8 and 12mm)	(Saute et al., 2021)
100, 120, 140 and 160 kg DM m^{-3}	experimental silos 7 L capacity	Marandu (*Brachiaria*) grass	The lower density silages showed greater gas production. Higher bulk density silos showed lower pH, and higher *in vitro* digestibility than lower density silos. Bulk density increase provided a reduction in NIDN, B3 fraction, NDF and ADF concentration.		(Camargo do Amaral et al., 2007)
Compaction pressure in compacted treatment 11. 66 kPa (density not stated)	13.6 L laboratory pipe silos (height, 0·75 m; internal diameter, 0.152 m	perennial ryegrass	Lower NDF and ADF and effluent production in compacted than in uncompacted silage	air infiltration effects also studied	(McEniry et al., 2007)

3.4 Density effect on the performance of silage additives

In the studies identified by the search strings applied, several types of additives were tested. Some were salt based chemicals, some were bacteria or enzymes and others were waste products from food processing factories. There were only a few studies, which included a combination of additive and density treatments. Fruit agrobusiness waste has been shown to reduce the positive effect of density on elephant grass silage fermentation (de Azevedo et al., 2017). Citric pulp has been shown to reduce Tanzania grass effluent losses more at higher densities than at lower densities, while there was a positive correlation between effluent losses and density in treatments without citric pulp (Tavares et al., 2009) (Table 5). Jungbluth et al. (2017) found that some lactobacterial inoculants or mixtures of lactobacteria prevented aerobic reheating of maize silage better at a high density than at a low density, while an additive consisting of sodium benzoate, potassium sorbate, sodium acetate prevented reheating and silage deterioration at both investigated densities. Also Kung et al. (2021) showed that lactobacterial inoculations improved the aerobic stability of maize silage more at high than at low density. However, Gallo et al. (2018) found that inoculation with a combination of hetero-fermentative and homo-fermentative lactobacteria had a positive effect on maize silage soluble crude protein content at a low density but a negative effect at a high density (Table 5).

Table 5. Effect of additives at different silage density

additive	density	type of silo	crop/ensiled material	finding	reference
passion fruit and mango by-products, banana waste	400, 500 and 600 kg green matter m^{-3}	experimental PVC silos 60 cm height 15 cm diameter	elephant grass (*Pennisetum purpureum*)	The fruit agrobusiness waste products decreased the positive effect of density on fermentation and microbial processes	(de Azevedo et al., 2017)
citric pulp	400, 500, 600, 700 and 900 kg m^{-3}	experimental PVC silos 4 and 8 kg capacity	Tanzania grass (*Panicum maximum* Jacq. cv. Tanzania I)	Negative effect of density on effluent losses when citric pulp was added; opposite effect in silage with no additive	(Tavares et al., 2009)
sodium benzoate, potassium sorbate, sodium acetate; mixed biological inoculant containing *Lactobacillus buchneri*, *L. plantarum*, and *Pediococcus acidilacti*; and a mixed biological inoculant containing *L. buchneri*, *L. plantarum*, and *L. rhamnosus*	196 kg DM m^{-3}; 261 kg DM m^{-3}	65 L buckets	maize	The biological inoculants prevented aerobic reheating at high density; the chemical additive prevented aerobic reheating at both densities	(Jungbluth et al., 2017)
A combination of *Lactobacillus buchneri* 40788 and *Pediococcus pentosaceus* 12455	180 kg DM m^{-3}; 240 kg DM m^{-3}	7.5 L silos	maize	inoculation improved aerobic stability more in 240 kg DM m^{-3} treatment than in 180 kg DM m^{-3} treatment	(Kung et al., 2021)
A combination of hetero-fermentative *Lactobacin buchneri* LB1819 and homo-fermentative *Lactococcus lactis* O224	132 +/- 6 kg DM m^{-3}; 186 +/- 6 kg DM m^{-3}	20 L plastic jars	maize	A positive inoculant effect on soluble crude protein at the high density; a negative effect at the low density	(Gallo et al., 2018)

4 Effect of type of storage

4.1 Effects on fermentation characteristics

Few studies were found that investigated the same silage material across silo types and these studies showed no or only small differences in fermentation characteristics between silo types. In maize, Jatkauskas et al. (2018) found a positive effect of lactic acid inoculants on lactic and acetic acid concentration and a decrease in the concentration of butyrate, ammonia nitrogen (NH3-N) and alcohols in silage maize in both bales and in mini silos. Da Silva et al. (2014) showed that sodium benzoate had a more positive effect on aerobic stability than *Lactobacillus buchneri* inoculation in bunker silos and laboratory silos. Similarly, Weng et al. (2021) found consistent reductions in aerobic yeast and mould growth of maize across laboratory, bale and bunker silos after dual *Lactobacillus plantarum* LP1028 and *Lactobacillus buchneri* inoculation. However, Xia et al. (2023) found that maize in silage bags had a higher lactic acid and dry matter contents and a lower pH value than maize in bunker silos and bales 9 days after opening, and in a study by Huffman et al. (2023) there was a higher relative abundance of *Leuconostocaceae* and pH in maize and grass legume mixtures in tower silos than in bunker silos. Another study showed higher lactic acid and lower butyric acid concentration in perennial ryegrass in vacuum packed bags than in glass jar silos (Hoedtke and Zeyner, 2011) (Table 6).

Table 6. Differences in fermentation characteristics between silo types

type of storage comparison	crop/plant material	main findings	comments	reference
small farm bucket silos and wrapped bales	alfalfa	A negligible difference in fermentation quality between silo types		(Li et al., 2023)
bunker silo, round bales, and silage bags	maize	Silage bags conserved higher lactic acid and dry matter contents and a lower pH value than other groups after 9 days of exposure ($p < 0.05$). The silage bags showed the longest aerobic stability (202 h).		(Xia et al., 2023)
tower and bunker silos	maize, grass legume mixtures	Tower silos had higher relative abundance of *Leuconostocaceae* ($p < 0.001$) and higher pH ($p < 0.001$) in corn and grass-legume silage.	Farm scale study	(Huffman et al., 2023)
glass preserving jars and vacuum-packed plastic bags	perennial ryegrass	Higher conc of lactic acid and lower butyric acid in plastic vacuum bags than in glass silos. No or only minor differences in other fermentation variables between silo types		(Hoedtke and Zeyner, 2011)
big (1.2 m diameter x 1.2 m height) bales or 3 L mini silos	maize	Viable lactic acid bacteria caused reduction in pH, a decrease in concentrations of butyrate, ammonia nitrogen and alcohols, and an increase in the concentrations of lactic and acetic acids in both big bale and laboratory silage.		(Jatkauskas et al., 2018)

type of storage comparison	crop/plant material	main findings	comments	reference
15-L laboratory silos, bunker silo	maize	Sodium benzoate resulted in a longer aerobic stability than *Lactobacillus buchneri* inoculated or uninoculated maize in both silo types.		(Da Silva et al., 2014)
bunker silage and bale silage controls with high and low chamber pressure	timothy dominated grass silage	Bunker shoulders were more infected by *Clostridium tyrobutyricum* than samples from bunker centres or from bales.		(Randby et al., 2020)
minisilos, 400 kg silo bags, bunker silo	maize	Positive effects of *Lactobacillus plantarum* LP1028 and *Lactobacillus buchneri* LBC1029 (dual purpose inoculants) both in mini-silos and in larger scaled silos. In bunkers the dual-purpose inoculants may double the aerobic stability in a bunker silo	Bunkers were smaller than usual farm scale bunkers	(Weng et al., 2021)

4.2 Effects on dry matter losses

Lactic acid bacteria inoculations have been shown to decrease DM losses from maize both in big bales and in laboratory silos (Jatkauskas et al., 2018). Sodium benzoate reduced bunker top layer DM losses of maize silage but inoculations with *Lactobacillus buchneri* did not, and there was no effect on maize DM losses in laboratory silos for either of these additives (Da Silva et al., 2014). Muck et al. (2015) showed higher DM losses from alfalfa ensiled in bunkers than in bags, a silo type which, in turn, resulted in higher alfalfa DM losses than oxygen limiting silos, while Shinners et al. (2009) reported no such differences in DM losses between alfalfa ensiled in large round and square bales wrapped either individually or in tubes. DM losses of timothy dominated grass silage have been found to be larger from bunker silos than from bales (Randby et al., 2020). Cai et al. (2020) reported higher DM spoilage of lactic acid inoculated napiergrass in bunker silos than in drum can silos after a 24 h delayed sealing, but found no such silo type effect on DM losses in uninoculated material or after a non-delayed sealing regardless of inoculation treatments (Table 7).

Table 7. Effect of silo type on dry matter losses

type of storage comparison	crop/plant material	main findings	comments	reference
round bales, square bales, tubes	alfalfa	No significant differences in DM losses between round and square bales, or bales wrapped individually or in a tube		(Shinners et al., 2009)
bunker, bag, tower	alfalfa	DM losses from the bag, bunker, and oxygen-limiting tower silos were 11 %, 17 %, and 4 %, respectively for 14-15-month storage.		(Muck et al., 2015)
bunker, bales	grass/clover mixture	Higher moulded wasted silage and DM losses from bunkers than from bales.	Density: bales: 109 kg DM m^{-3} (untreated) 114 kg DM m^{-3} (treated); bunkers: 159 kg DM m^{-3} (untreated) 170 vs. 159 kg DM m^{-3} (treated)	(Randby and Bakken, 2021)
big (1.2 m diameter x 1.2 m height) bales or 3 L mini silos	maize	Viable lactic acid bacteria caused a decrease in DM loss in both big bale and laboratory silage.		(Jatkauskas et al., 2018)
15-L laboratory silos, bunker silo	maize	Sodium benzoate additives reduced DM losses at the top layer of maize in bunker silos, but no such effect was found in 15 L laboratory silos.		(Da Silva et al., 2014)
bunker, 150-L polyethylene drum can silos	napier grass	Higher DM spoilage of lactic acid inoculated (Chikuso-1) materials from bunker silos than from drum can silos after a delayed sealing. No effect of silo type on spoilage of uninoculated silage regardless of sealing delay time. No effect of silo type on DM loss after quick sealing regardless of inoculation treatment		(Cai et al., 2020)
Bunker silage and bale silage controls with high and low chamber pressure	timothy dominated grass silage	higher silage losses from bunkers than from bales.		(Randby et al., 2020)

4.3 Effects on nutritive value

Weng *et al.* (2021) showed no effect of a dual a dual *Lactobacillus plantarum* LP1028 and *Lactobacillus buchneri* on maize nutritive values neither in minisilos, bales nor bunker silos. Alfalfa and grass ensiled in angled wedge silos had a lower ADF content than the same crops ensiled in horizontal and vertical layer silos in a farm scale study (Ruppel et al., 1995). In another farm silo type comparison there was lower CP and fibre content in alfalfa silage in bunker silos than in bags or oxygen limiting silos in one year out of two (Muck et al., 2015). However, Shinners et al. (2009) found no differences in nutritive value between alfalfa ensiled in the different bale types described in 4.2. Neither did Li et al. (2023) find any difference in alfalfa nutritive value in small farm bucket silos or in wrapped bales. Randby and Bakken (2021) showed that formic- and propionic acid-based additives increased the content of fibre bound protein in grass and clover mixtures in round bales but not in bunkers.

Table 8. Effect of silo type nutritive value

type of storage comparison	crop/plant material	main findings	comments	reference
bunker, wedge (different types)	alfalfa, grass	Angled wedge silos lower acid detergent fibre (ADF) content than horizontal and vertical layer silos	farm samplings	(Ruppel *et al.*, 1995)
minisilos, 400 kg silo bags, bunker silo	maize	A dual-purpose inoculant had no effect on the nutritive value in any of the silos.		(Weng *et al.*, 2021)
round bales, square bales, tubes	alfalfa	No significant differences in nutrient retention between round and square bales, or bales wrapped individually or in a tube, or high and low moisture ranges.		(Shinners *et al.*, 2009)
bunker, bag, tower	alfalfa	Lower crude protein and fibre fractions in bunker silos than in the other silos one year out of two.		(Muck *et al.*, 2015)
small farm bucket silos, wrapped bales	alfalfa	A negligible difference in fermentation quality between silo types. All additives increased the preservation of the nutritive value		(Li *et al.*, 2023)
bunker, bales	grass/clover mixture	Formic and propionic based additives increased fibre bound protein in bales, but not in bunkers	Density: bales: 109 kg DM m^{-3} (untreated) 114 kg DM m^{-3} (treated); bunkers: 159 kg DM m^{-3} (untreated) 170 vs. 159 kg DM m^{-3} (treated)	(Randby and Bakken, 2021)

4.4 Effects on mycotoxin content

Baliukoniene et al. (2012) and Jovaisiene et al. (2016) showed higher contamination of aflatoxin and deoxynivalenol and lower contamination of zearalenone in bales than in trenches in a farm scale survey of grass, clover and maize silage, but also underlined that mycotoxin contamination differed more between crops than between silo types. However, Venslovas et al. (2021) found higher concentrations of aflatoxin B1 in samples of maize and grass silage from trench silos than from clamp silos and bales, and no difference in the concentration of other mycotoxins between silo types. In another farm sampling study, silage from bales contained higher concentrations of enniatin B than silage from pits did, while there were no differences in other analyzed mycotoxins between these silo types (McElhinney et al., 2016). On the other hand, McElhinney et al. (2015) found no significant differences in the concentration of any analyzed mycotoxins between pit and bale silage, which mostly consisted of perennial ryegrass, in another farm sampling study. In a controlled study, maize in silage bags had a lower concentration of aflatoxin B1, trichothecenes and fumonisin B1 than maize in bunker silos and bales nine days after exposure but not after shorter times of exposure (Xia et al., 2023).

Table 9. Effect of silo type on mycotoxin concentration

type of storage comparison	crop/plant material	main findings	comments	reference
bales, horizontal pit silos	baled silage dominated by perennial ryegrass; pit silage 85 % grass and 15 % maize	No differences in mycotoxin levels between bale and pit silos. No effect of position in pit on mycotoxin contamination	farm samplings	(McElhinney et al., 2015)
bales, trenches	grass mixtures, clover, maize	Higher contamination of aflatoxin and deoxynivalenol and lower contamination of zearalenone in bales than in trenches. However, larger differences in mycotoxin contamination between crops than between silo types	farm samplings	(Baliukoniene et al., 2012)
bales, trenches	grass, grass legume mixtures, maize	Highest aflatoxin and deoxynivalenol contamination levels in ryegrass silage from bales, and highest zearalenone in maize from trenches	farm samplings	(Jovaisiene et al., 2016)
bunker silo, round bales, and silage bags	maize	The concentrations of aflatoxin B1, trichothecenes and fumonisin B1 were significantly lower in silage bags after 9 days of exposure than in the other silo types		(Xia et al., 2023)
trenches, clamps, bales	maize and forage grass	Highest aflatoxin B1 (AFB1) concentration (10.9 +/- 1.1 mu g kg^{-1}) was found in trench silos, while in clamps and bales aflatoxin B1 (AFB1) concentration was 48 % and 44 % lower respectively	On farm sampling	(Venslovas et al., 2021)
bales, pit silos	round bales: grass, pit silage: grass and a few maize samples	Bales contained higher concentrations of enniatin B than pit silage in one year of two. No differences in the concentration of other mycotoxins between silo types	farm samplings	(McElhinney et al., 2016)

4.5 Effects of bale wrapping and silo coverage (number of wrappings, type of wrapping films)

Sealing of both bales and bunker silos with oxygen barrier film instead of conventional polyethylene film has been shown to improve fermentation characteristics and reduce DM losses in a number of field experiments with maize and alfalfa silage (Table 10). However, the effect of the number of layers of bale wrappings on silage characteristics has varied between experiments (Table 10).

Table 10. Effects of wrapping and coverage on silage characteristics and DM losses

type of storage	crop/plant material	main findings	reference
bunker silo	maize	The top layer of silage conserved under oxygen barrier film had a) higher lactic acid content and lower pH, b) lower counts of yeasts, molds, and aerobic and anaerobic spore-formers, c) higher aerobic stability d) lower DM losses than the silage conserved under polyethylene film.	(Borreani and Tabacco, 2014)
bunker silo	maize	Lower pH in peripheral layer, and less losses from silage under oxygen barrier film coverage than in silage under polyethylene film.	(Borreani et al., 2007)
round bales	alfalfa	Lower storage DM losses from bales with oxygen barrier film than from bales with polyethylene film regardless of number of film layers. Lower mould surface coverage in bales wrapped with 4, 6 or 8 layers of oxygen barrier film than in bales wrapped with polyethylene film.	(Borreani and Tabacco, 2008)
bales	alfalfa	Four layers of wrappings with oxygen barrier films with 18- or 370-fold lower permeability than polyethylene film reduced DM losses and mould spoilage in comparison to the polyethylene film.	(Borreani and Tabacco, 2010)
120- L plastic silos	maize	4-day delayed sealing a) increased yeast counts, b) decreased water soluble carbohydrates, c) increased DM losses, d) promoted the formation of ethyl esters, and e) decreased aerobic stability	(Bruning et al., 2018)
bales	alfalfa	After harvest in July, the bales wrapped with two layers had higher post storage NDF, ADF and acid detergent lignin concentration than 4- and 6-layer bales. No consistent differences between wrapping treatments after harvest in September	(Hancock and Collins, 2006)
bales	alfalfa	Increased number of film layers resulted in decrease in mould and yeast counts	(Keller et al., 1998)

5 Synthesis and research outlook

Most studies showed positive correlations between silage density and fermentation and feed value, and negative correlations between silage density and DM losses, indicating that farm measures to increase silage density would have mostly favourable consequences for animal feed production. There is, however, a great variation in the magnitude of these effects. The negative effect of oxygen-barrier films on pH, yeast and mould counts, and DM losses in peripherical bunker silo layers and in bales indicate that such films to some extent could compensate for a low density. On the contrary, there are no consistent indications that effects of additives are linked to silage density. Moreover, the effect of silage density on feed value is somewhat difficult to interpret. First, negative correlations between of neutral detergent and acid detergent fibre content (NDF; ADF) and density in farm surveys could be caused by low fibre content facilitating compaction (Krüger et al., 2020), rather than a positive effect of compaction on fibre content. Second, the feed value of fibre and protein is largely depending on the role of the silage in the total feeding plan and what type of animal the silage is intended for.

The silo type comparisons indicated that silage bags and bales can be favorable to silage quality and dry matter preservation compared to bunker silos. Nevertheless, comparisons performed so far should be supplemented by new ones with crops, notably maize, with other properties than forage grass and legumes. The reviewed density effects were conducted across a wide range of materials, silo types and scales. There are a limited number of comparisons across scales (da Silva et al., 2014; Jatkauskas et al., 2018; Li et al., 2023; Weng et al 2021), which showed rather similar fermentation characteristics and DM losses both at laboratory and farm/field scale. Further experiments at farm scale which also keep track of the underlying reasons for density effects on silage such as porosity and air permeability in different silo types and ensiled materials could generate more complete results that are applicable to farm scale conditions. New studies on additives could consider the cost and availability of the additive and how easy it is to handle, together with more detailed information about its mode of action during silage fermentation. Further controlled studies of causes for incidences of mycotoxins in silages could consider the toxicity and growth and dispersal pattern differences between toxin producing fungi. In total, such experiments could in turn serve as a better basis for silage density and silo type recommendations.

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