

# Ensiling for anaerobic digestion (AD): a review of key considerations to maximise methane yields

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## Abstract

Growth in anaerobic digestion (AD) has expanded the use of silage to preserve crops intended for renewable energy generation. Preservation of seasonal crops and their residues is critical in a process that needs continuous feeding. Whilst the impact of different crops and harvesting times on methane formation is relatively well understood, to date the specific considerations for maximising methane yields through management practice have been largely ignored. The present paper reviews the current state of knowledge on silage practice for biogas production and specifically on the factors affecting methane yields of ensiled crops, as well as their influence on the silage quality, and provides suggestions for further research in the field. Data shows that ensiling is able to conserve 93% of crops gross energy when good practices are followed. Shorter chop length (7-10 mm), lower DM feedstock (20-35%) and lower compaction values (less than 250 kg/m<sup>3</sup>) are used to achieve higher biogas yields. Increase biogas production can also be obtained by managing the organic acids production with the preferential formation of acetic acid and ethanol instead of lactic acid via enzymatic or microbial additives. The review outcomes show that more research is required to provide a clear-cut distinction between the requirements for ensiling crops for AD versus crops for animal feed.

## Highlights

- Higher biogas achieved with lower DM feedstock and lower compaction values
- Shorter chop length produced higher biogas yields
- Increased biogas yields obtained with additives and a wider range of acids
- Research need for specialised silage bioadditives targeted at biogas production
- Silage of agricultural residues needs a different approach

## Keywords

Biogas, methane yield, dry matter, quality silage, storage systems

## List of abbreviations

VS: Volatile solids

LAB: lactic acid bacteria

DM: Dry matter

WSC: water soluble carbohydrates

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## 1 Introduction

Energy crops produce some of the highest biogas yields as compared to other feedstocks [1] and have for some time now increased the AD (AD) feedstock base [2]. This growth has expanded the use of silage, traditionally used for preserving crops for animal feed, to crops intended for renewable energy generation [3,4]. Preservation of seasonal crops and their residues is critical in a process that needs continuous feeding [5,6]. However, for animal feed the main objective of silage is to preserve crops nutritive value, whilst minimising methane production in the animal rumen. Whereas, in anaerobic digestion the silage process should be focused on preserving the crops for achieving the highest methane yields possible [7,8]. Crops methane yield ( $\text{m}^3\text{CH}_4 \cdot \text{ha}^{-1}$ ) depends primarily upon the biomethane potential ( $\text{m}^3\text{CH}_4 \cdot \text{t}^{-1}$ ) of the feedstock (e.g. its composition) and the biomass yield ( $\text{t} \cdot \text{ha}^{-1}$ ) [9]. Both of these parameters can be influenced by different factors throughout the feedstock chain such as cultivation, harvest and storage methods [9–11]. Whilst the impact of different crops and harvesting times on methane formation is relatively well understood [2,9,10] to date the specific considerations for maximising methane yields through silage management practice have been largely ignored. The present review consolidates the current state of knowledge and highlights areas of future research in relation to silage practice for biogas production. Maximum methane yields can be achieved with high-quality silage about different crops might require different storage management practice [7,8]. In addition, silage of agricultural waste should be taken into consideration to couple renewable biogas production and sustainable waste management. The review will focus on four energy crops: maize, grass, whole crop cereals and beet, which are the dominating energy crops used in the UK [3,12]. Specifically, an in-depth review of the current understanding of the factors that affect the energy yields of ensiled crops, as well as the influence of key parameters on the silage quality such as characteristics of the crop at ensiling, silo design and silage management, in addition to silage of agricultural waste. Finally, a number of gaps in research related to silage for AD will be identified and recommendations for future studies proposed. Up to date references on biogas production from silage crops focus on the biogas yields of material rather than the management and storage conditions of the feedstock. To the best of our knowledge this is the first review that focuses on crop ensiling for energy production, with specific focus on management practices for maximising methane yields.

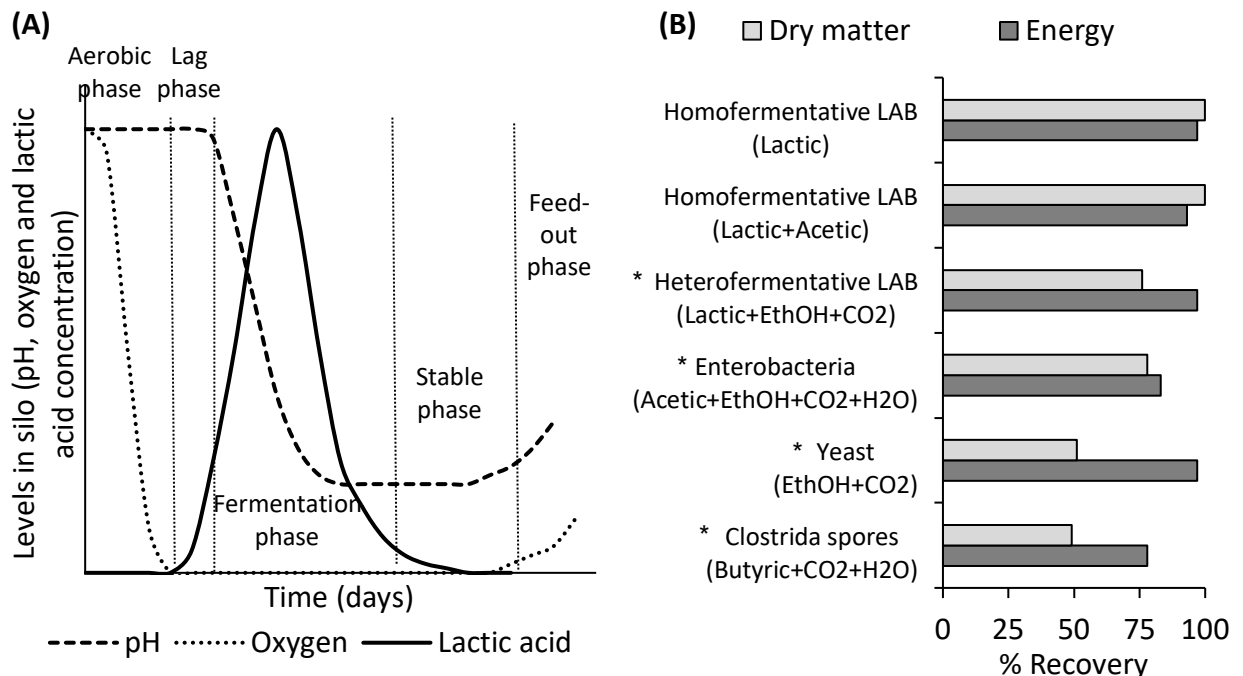
## 2 Ensiling for Anaerobic Digestion

Ensiling consists of various biochemical processes, each of which directly or indirectly affects biogas production by changing the properties of the feedstock [13,14]. The process functions through the production of organic acids, such as lactic and acetic acid, which reduce the pH of the feedstock causing its preservation against the growth of fungi, bacteria and yeasts [15]. There are four phases that occur during silage fermentation: an initial aerobic phase, followed by a lag phase and an anaerobic phase. At the end of the anaerobic phase the ensiling process has been largely concluded, thus leading to the stable phase, which lasts until the silage is

required for use and the feed-out phase starts [5,16]. It is important that all four phases are well-understood to minimise potential reductions in biogas yields (Figure 1A). The aerobic phase occurs during the chopping, filling, and packing steps [5,17]. During this phase, oxygen is eliminated as a result of respiration. Respiration is a 'wasteful' process during which aerobic microorganisms uptake sugars competing with lactic acid bacteria (LAB) and the AD anaerobic bacteria. Therefore, aerobic processes causes losses of energy and dry matter (DM) [5,16]. Figure 1B provides a summary of mass and energy recovery depending on the microbial groups abovementioned.

The anaerobic phase (or fermentation phase) is dominated by homofermentative or heterofermentative LAB which produce a drop in pH, from 5.0 to 3.7 due to increasing lactic acid concentrations [5,18]. At this pH level the growth of harmful microorganisms, mainly enterobacteria, clostridia and yeasts, is inhibited, energy losses are limited in both cases whereas biomass recovery is lower if heterofermentative bacteria are able to thrive (first three set of bars in figure 1B) [16,19,20].

The stable phase starts when the growth of LAB stops [5,18]. At this point, the LAB are dominant and lactic acid is the predominant end-product formed. If the silo is properly sealed, DM and energy losses in this phase should be minimal as no additional changes should be taking place [5,20,21].



**Figure 1. A.** Changes during ensilage fermentations of pH, oxygen and lactic acid (modified from [16]). **B.** Mass and energy recovery from fermentation during ensiling. (adapted from [25]). \* Undesirable pathways for animal feed

The feed-out phase begins when the silo is opened and continues until all the silage has been removed and fed into the AD plant [5,19]. During this final phase, the ensiled crop face is exposed to oxygen, which supports yeast growth. At the same time, the silage pH increases, allowing previously inhibited fungi and bacteria to produce different fermentation products, with dry matter losses up to 50% [17,21] and reduce silage quality for animal feed [5,21]. However, as figure 1B clearly demonstrates, this is not necessarily the case for energy production (bottom set of bars in figure 1B), where the presence of other acids then lactic can be beneficial to biogas production and the AD process [19,22,23,24]. Butyric acid, higher volatile fatty acids and alcohols are associated with high theoretical methane yields based on their elemental composition [11,24]. Consequently, silage that was traditionally considered to be poor output for animal feed may be good AD feedstock and reach higher methane potentials.

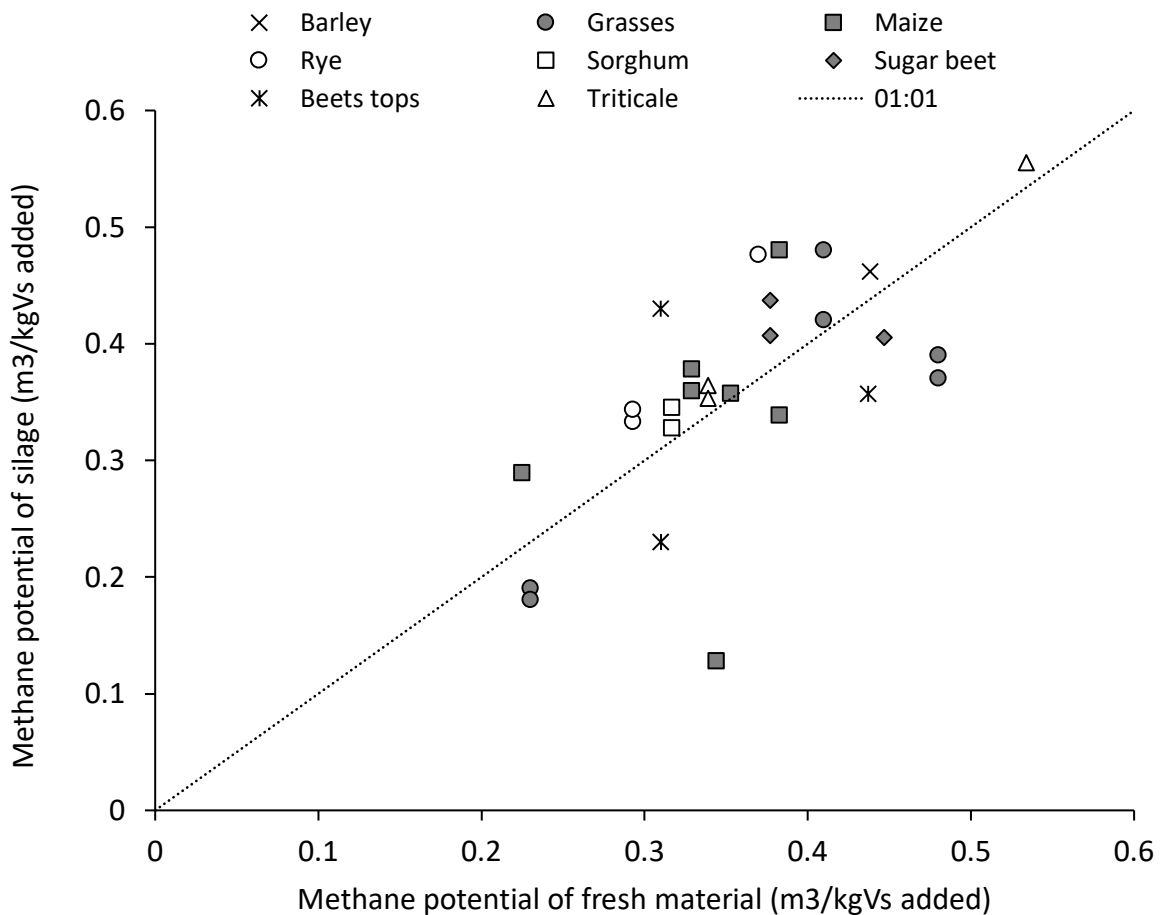
Ensiling has been reported to increase methane yields as compared to fresh matter, based on volatile solids (VS) [10,26–32]. However, there are a number of studies showing no significant differences in methane yields between ensiled and fresh crops [32,25].

Figure 2 shows the impact of ensiling energy crops without additives on methane production using the published data of comparative studies between silage and fresh material [10,11,20,25,27,29-31,33] (Table 1S). A paired two tailed t-test used to evaluate the significance of the difference between biogas from silage and from the same fresh material showed that, although silage produced slightly more biogas than the fresh material, the difference between the two data sets was not significant ( $p = 0.224$ ). Several authors reported that some fermentation products have the potential to enhance methane yield of silage crops, especially those derived from undesirable microbial activity [19,20,26].

Notwithstanding this, the methane yield of silage crops ( $\text{m}^3\text{CH}_4 \cdot \text{ha}^{-1}$ ) does not only depend on the methane potential of the feedstock, it also takes into consideration the field biomass yield ( $\text{t} \cdot \text{ha}^{-1}$ ) [9]. When considering silage for biogas production it is important to compare methane yield per hectare, because DM losses due to the formation of undesirable organic acids may be compensated by improved crop digestibility [34]. For example, fresh beets showed less biogas potential than other cereal and forages. However, after ensiling, beets showed better biogas potential and methane yields than other crops due to the increasing ethanol formation during ensiling Weissbach (2009).

The effect of storage time on methane yields has also been studied by [11,29,31,35]. All four studies reported that longer storage periods have a positive effect on methane yield. This is attributed to the fact that in well preserved silage the concentration of ethanol increases as a function of the age of silage [31,36]. An analysis of the data reported in figure 2 showed that these improvements were not significant. Of note is that, some researchers have stated that storage requirements may not be as stringent when using silage for AD as compared to when using silage for animal feed [37]. This is because factors of importance in animal nutrition, such as protein content, digestibility, palatability or DM intake, have little consequence in AD,

where preservation of energy during storage is the main concern. In fact, ensiling has been shown to conserve 93% of the crops gross energy when good practices are followed [38]. On the other hand, poor silage management practices in all phases have been associated with energy losses as high as 40% [38]. However, there is a dearth of information about the degree of dependence between well preserved silage and methane yield and further studies are required to fully understand the link that exists [7,39,40].



**Figure 2.** Impact of ensiling without additives on methane formation of maize, grasses beet tops, barley, rye, triticale, sorghum, sugar beets and beets with different storage times (from 3 to 12 months) [10,11,20,25,27,29-31,33]. Data used for the table are available in supplementary material (T1S).

### 3 Key considerations to maximise silage methane yields

The primary objective in preserving crops for biogas production is to prevent energy losses during storage [13]. The specific characteristics of good quality silage will depend upon the specific crop being ensiled whilst the amount of losses and the final silage quality will be

influenced by a number of factors, including: fermentation profile, moisture content and chop length of the feedstock, use of additives, silo style and silo management.

### *3.1 Fermentation profile*

Data reported in table 1 outlines silage fermentation profiles found in literature to obtain proper preservation of maize, grass, whole crop cereal and beet for animal feed and biogas production. There are some considerable differences in target values between the various crops listed, which indicate the importance of determining crop specific targets, rather than universal targets. The pH is usually lower for materials with higher water content. A faster pH decrease will produce more water soluble carbohydrates in the silage mass and therefore more biogas [41]. Higher lactic acid levels indicate good fermentation and lead to better preservation for animal feed. Whereas lower levels indicate the silage was not harvested at the proper moisture content, chopped to incorrect length, not well packed or exposed to oxygen, optimal for biogas production. High concentration of acetic acid may indicate the silage was not packed densely or quickly enough, was not covered appropriately, or was too dry, not ideal for animal feed but good for biogas production. High level of acetic acid can also be produced by additives (hetero LAB) and produce higher biogas yields [42, 43] . Similarly, high levels of butyric acid, which indicate clostridia fermentation, are not recommended for animal feed but can be good for energy production [41,44]. The theoretical CH<sub>4</sub> content (expressed as a proportion of biogas volume) of butyric acid, propionic acid and ethanol are 0.63, 0.58 and 0.75 respectively [45]. Hence increased concentrations of compounds like ethanol [46] and butyric [44] are able to produce higher specific CH<sub>4</sub> yield.

### *3.2 Moisture Content*

Crops for biogas production are usually harvested at a less mature stage of growth than for animal feeding since the content of lignocellulose, which is not easily degraded by anaerobic processes, increases with time [33]. In general, it could be said that moist material is preferred for the anaerobic digestion process [33, 42]. When harvested crops, like grass, have higher moisture content than is desirable, the cut material is left in the field in order for it to wilt. Table 1 compares the dry matter content suggested in the literature for crops for biogas production and animal nutrition.

From a technical point of view, lower DM contents (below 25–30%) lead to formation and release of silage effluent associated with additional mass [60] and energy losses [8]. This can be counteracted by collecting and reusing leachate for biogas production [60]. High DM contents, on the other hand, can hinder sufficient compaction of the crop material within the silo and promote aerobic deterioration at feed-out [60] or cause a negative impact upon storage stability [50].

**Table 1.** Target values of fermentation characteristics [6,8,11,21,23,29,33,41,45,47–59].

	<b>Silage for biogas production</b>	<b>Silage for animal feed</b>
<b>Organic acid/alcohol range (g/kgDM)</b>		
Maize	Lactic 19-63	Lactic 40-70
	Acetic 16-39	Acetic 10-30
	Butyric 1.3-45	Butyric <1.3
	Ethanol 12-20	Ethanol N/A
	pH 3.8-4.2	pH <4.2
Grass	Lactic 30-50	Lactic 80-120
	Acetic 20-50	Acetic 20-50
	Butyric 1-8	Butyric <10
	Ethanol 7-16	Ethanol N/A
	pH 4.5	pH <4.5
Whole crop cereal	Lactic 20-55	Lactic 30-60
	Acetic 16-39	Acetic 10-30
	Butyric 1.3-11	Butyric <3
	Ethanol 12-31	Ethanol N/A
	pH 3.8-4.0	pH <4.2
Beet	Lactic 9-52	Lactic >30
	Acetic 10-60	Acetic <15
	Butyric 0-4	Butyric <0.2
	Ethanol 28-48	Ethanol N/A
	pH 3.7-3.8	pH <4.0
<b>DM range (%)</b>		
Maize	27-31	30-35
Grass	26-30	30-45
Whole crop cereal	30-36	33-50
Beet	20-23	25
<b>Chop length range (mm)</b>		
Maize	7-10	12-15
Grass	7-11	10-25
Whole crop cereal	7-12	20-50
Beet	Na	Na
<b>Compaction (kg/m<sup>3</sup>)</b>		
Maize	230	>400
Grass	210	>250
Whole crop cereal	230	>251
Beet	Na	na

From a biological point of view, clostridia are more sensitive to acidity at a decreasing water activity, thus, a low DM content necessitates a lower pH of the silage and higher lactic acid formation for inhibition of clostridia [31]. Furthermore, for an effective fermentation during silage making the dry matter content of the crops being ensiled should contain water-soluble carbohydrates (such as sucrose, fructose and glucose) at an optimal range between 60 and 80g/kg<sub>DM</sub> [19]. Biomass containing water-soluble carbohydrates within this range will possess sufficient readily available substrate for fermentation with a corresponding low buffering capacity for pH decrease.

A DM content of 28–40% is often stated as a rough estimate for optimal ensiling conditions. However, it is clear that the critical DM content required to ensure good silage is feedstocks dependent and relates to chemical characteristics such as available water-soluble carbohydrates and buffering capacity [31].

### *3.3 Chop Length*

Shorter feedstock chop lengths are considered to be beneficial for preservation because they enhance compaction and oxygen elimination in the silage. For cattle feeding, the feed needs to be long enough to float in the rumen and maintain the rumen fibre, which is an important factor in the prevention of digestive disorders [61]. However, for biogas production a shorter length has a positive effect on the silage degradability in the digester increasing lactic acid fermentation yields [62]. This is because shorter lengths offer a larger surface area for the microorganisms to act upon to break down the crop, thus facilitating biogas production and reduce retention times. The optimal chop length varies depending on the crop ensiled (Table 1) although, there seems to be a minimal value beyond which chopping to shorter sizes will not improve the overall process economy [11]. This is largely related to the increased expenditure associated to the additional energy demand that shorter cuts involve. In fact, it is not yet clear at what level the additional benefit from increased methane yields is eclipsed by the additional cost [6,62]. Grass feedstock is particularly controversial and several studies have suggested different chop lengths. For example, studies on a Finnish farm investigated the use of grass chop lengths at 5, 10 and 20 mm and the grass silage yielded most methane at the 10 mm size. In contrast, experiments in Germany with grass silage demonstrated higher methane yields when using shorter chopping (4mm) [6].

Of note is that in the case of sugar beets, it is suggested that the whole beet is ensiled and then chopped before it is fed into the digester [60,63]. This is because chopped beets produce significantly more effluent than whole beets. Therefore, the risk of nutrient losses through uncontrolled effluent is notably increased [63].

### *3.4 Additives*

Additives are commonly added during the silage making process, since in field conditions, adequate fermentation conditions are not always guaranteed. A good additive for energy



crops should enhance the process yields whilst minimising storage losses [34]. The additives most commonly used fall into three classes [13]: (1) Chemical preservatives (e.g. formic acid), which suppress undesirable microbiota, such as Clostridia; (2) Lactic acid bacteria (LAB), which accelerate lactic acid fermentation; and, (3) Molasses, which increase fermentable carbohydrates. Most of these additives (except hetero LAB) have been shown to reduce DM losses during ensiling yet have no significant effect on methane production [11,29,30,45]. This makes sense, because when silage is destined for animal feed, in contrast with biogas production, the minimum formation of methane in the rumen is desirable. In fact, in comparing the response of farmers growing crops for AD and animal feeds, none of the AD farmers reported the use of additives, whilst animal feed farmers reported a 25% usage of additives [64].

Heterofermentative LAB have a positive effect on methane yields [42]. This is attributed to the increased production of acetic acid by the hetero LAB, which function as a precursor to methane production [40,45,48]. In many cases the additional increase of methane production could be not compensated by the cost of additive application [34]. It is suggested, that a more complex additive with homo and hetero LAB as well as enzymes or bacteria may be the most appropriate for use in silage destined for AD [48]. This is because in addition to increasing lactic acid production they may then later facilitate the hydrolysis process during AD. Yet, further research is required in order to identify the most effective combination for improving methane yields during AD.

### *3.5 Silo type*

There are several types of silos in use for silage making. Silage clamps, silage bags and wrapped bales are the most commonly used storage systems for both silage that is intended for AD and animal feed. The various types of silo constructions are compared in Table 2. Good quality silage can generally be obtained using any of the systems, as long as the design and management of the silo is appropriate.

In terms of silage clamps, these may range from a walled clamp (bunker) to a simple stack (field clamp). Walled clamps consist of a permanent structure constructed above ground with three walls. The walls are usually made of concrete, steel or railway sleepers [65] and floors are generally made of concrete with drainage channels to facilitate the collection of effluent. This effluent, due to its high organic content, could pose environmental problems but also energy losses. Maize, grass and cereal silage generally produce little effluent, whereas crops with higher moisture content, such as beets, generate higher amounts of effluent [51]. The effluent has a high energy content so, especially for biogas production it is important to capture and feed this effluent back to the digester [63].

The clamp design plays an important role in silage making. Specifically, the wall slope and height and the exposed faced are two of the critical design factors that affect silage quality as they affect the packing ability. Sloped walls and high walls have been shown to facilitate

consolidation [65, 66]. Additionally, by reducing the exposed face area clamp losses are minimized [68]. Hence, clamps should be sized to match the recommended feeding rates shown in Table 3. The importance of reducing the exposed face seems to be well understood by farmers producing silage. In fact, in the study on current UK practices by farmers producing silage [64], the most common change that farmers would implement if they were to re-design their silo, was to build narrower clamps or to install dividing walls to their existing clamps.

The inexpensive alternative to a walled clamps/bunkers are field clamps (unwalled clamps or piles). Field clamps consist of a silage pile covered with plastic. Since there are no walls, the height of these kind of clamps is limited for safety reasons and this means that the required level of compaction often cannot be achieved [65]. Field clamps have higher DM losses than bunkers because the exposed face is much bigger. There is also a higher risk of achieving poor quality silage if the recommended practices are not followed [51].

An alternative to clamps is to use silo bags (e.g., American Ag Bag) or wrapped bales. Wrapped bales and pressed bag silages have created more flexibility in silage making [69]. Various experiments prove that ensiling in bags results in low DM losses due to the rapid exclusion of air [48]. Wrapped bales are suitable for small batches [70]. Therefore, they could be an appropriate alternative for small-scale plants. However, even though high quality silage can be made with wrapped bales, fermentation is somewhat restricted relative to fermentation in other silo types [68]. The main disadvantage of both systems is the high storage cost per ton of silage [65]. Additionally, ensiling beet in bales risks poor fermentation and an increase in DM losses because of increased moisture content [65]. However, the development of these systems is ongoing, in order to help them produce more consistent silage and to make them more efficient [69].

A major determinant for silo type used is the volume of silage that is required. Clamps seem to be the best option when considering large quantities of silage. Bags could also be a good option for farmers ensiling around 10,000 tonnes [71]. In the UK AD farmers generally produce much larger volumes of silage than those who grow crops for animal feed and the majority of the AD farmers (92%) have bunker silos, whilst 75% of animal feed farmers use bales [64]. However, the literature available to date does not reflect this difference between the sizes of farms and silo types used by farmers producing silage for AD and those producing silage for animal feed. The difference is due to two reasons: firstly, cattle in the UK will generally eat silage during the winter, when they are kept indoors, while AD plants will use silage all year round. Secondly, AD plants generally require more silage per day than the cattle.

**Table 2.** Comparison of silo structure types [65, 71]

<b>Criteria</b>	<b>Walled Clamp/Bunker</b>	<b>Field Clamp/Pile</b>	<b>Silage/Ag-Bag</b>	<b>Wrapped Bale</b>
<b>Construction cost</b>	High	Low	Low	Low
<b>Cost/ tonne of storage DM</b>	Low	Low	High	High
<b>Flexibility and capacity</b>	Inflexible storage Highest capacity	Flexibility on pile quantity	Flexible with store sitting Capacity can be adjusted based on yield	Suitable for small batches Capacity can be adjusted based on yield
<b>Footprint</b>	The smallest	Larger than in bunkers	Larger than bunker and pile	The largest
<b>Durability</b>	Long lasting	Better for short storage periods	Not suitable for storage > 3 years	Not suitable for storage > 12 months
<b>Suitable crops</b>	All crops	All crops	All crops	Not suitable for high moisture crops
<b>Machinery required</b>	Conventional farm equipment	Conventional farm equipment	Specialized equipment	Conventional farm equipment
<b>Compaction achieved</b>	Good (better with slanted wall)	Lower density than bunkers	Adequate, but lower than bunkers	Adequate
<b>DM losses expected</b>	Higher than bags	The highest	The lowest	Higher than bags
<b>Labour requirements for filling</b>	More than for bags and bales	More than for bags and bales	Modest	The least
<b>Exposed surface face at feeding</b>	Large	The largest	The smallest	Small
<b>Management issues</b>	Care in filling and packing	Difficult packing Good management is critical	Bags are easy to damage (vulnerable to spoilage losses)	Damage can occur when storing and moving bales (vulnerable to spoilage losses)

## 4 Practical implications of this study, Recommendations and Future work

### 4.1 Practical implications

This review has consolidated current knowledge in the field of silage for AD and confirmed that the method of quality evaluation for biogas production should be slightly different than for animal feeding and that new process parameters need to be defined. The initial analysis of these parameters include:

1. Dry matter content should be lower (28–40%) and chopping lengths should be shorter (7–12 mm) for AD silage than for conventional silage for biological and technical reasons.
2. Hetero LAB additives are the only conventional additive that are able to reduce energy losses during ensiling.
3. Leachate collection and reuse is a critical for energy loss minimisation because of its high energy content.
4. Storage system for AD is directly related to the size of farm. Clamp/bunker are good for achieving good compaction, not so crucial for AD silage. Cheaper options such as bags can be a good alternative.
5. The use of an oxygen barrier film is recommended to inhibit the growth of microorganisms responsible for aerobic deterioration.

More focused studies are needed to determine specific requirements of AD silage and to determine best-practice for its production and management. To date, available data is largely lacking, and where it is available this is generally from single studies. Consequently, further work is needed to determine the target values for different types of silage for AD, and the impact of the various parameters on methane yields.

### 4.2 Recommendations for silo management

Most of the subject matter surrounding the management of silos presumes that the key factors involved are similar to those involved with the management of silage for animal feed. Therefore, many of the important silage management factors focus on getting to the stable face quickly and restricting oxygen exposure at the feed out. The procedures depend on the equipment available and the silo structure type (Table 3).

*Filling and compaction:* Filling the silo at the recommended DM content and chop length improves compaction and prevents the ingress of air. The expected densities when ensiling at optimal conditions are shown in Table 1 and differ for the two uses. The silo should be filled as rapidly as possible. In large clamps, where the filling process takes several days, the material should be compacted with the progressive wedge technique. In this way the current day material will be ‘sealed’ by the next day material, thus minimising aerobic deterioration [72].

*Sealing:* Well-sealed silos help to minimise aerobic losses during storage [72]. In clamps, how well the silo is sealed depends on the cover material used and how it is held in place. The

standard material used is polyethylene film. However, recent studies on oxygen barrier films [74-76] found that silage sealed with oxygen barrier film have significantly less DM losses in comparison with the same silage covered with polyethylene. Similarly, [73] showed that the oxygen barrier film is a better inhibitor of microorganisms responsible for aerobic deterioration.

**Table 3.** Silo management practices to minimize energy losses depending on the silo structure (W = Winter, S = Summer) [74,75].

<b>Process</b>	<b>Walled Clamp/Bunker</b>	<b>Field Clamp/Pile</b>	<b>Silage/Ag-Bag</b>	<b>Wrapped Bale</b>
<b>Filling</b>	Chop at correct length	Chop at correct length	Chop at correct length	Optimal DM
	Optimal DM	Optimal DM	Optimal DM	
	Rapid fill	Rapid fill	Rapid fill	
	Progressive wedge technique	Progressive wedge technique		
<b>Compaction</b>	Compress with tractor during filling	Compress mechanically during filling	Set filling machine for high compaction	Bale tightly
	Immediately after filling	Immediately after filling	While it is filled	Immediately after baling
<b>Sealing</b>	Cover with plastic	Cover with plastic		
	seal ends and sides carefully	seal ends and sides carefully	Seal ends carefully	Wrap or seal carefully
<b>Storage</b>	Check every two weeks	Check every two weeks	Check every two weeks	Check every two weeks
	Seal cracks in wall, repair holes in plastic cover	Repair holes in plastic cover	Repair damaged bags	Repair damaged bags
<b>Feed out</b>	10 cm/day (W)	10 cm/day (W)	10 cm/day (W)	
	16cm/day (S)	16cm/day (S)	16cm/day (S)	

*Feeding out:* As soon as the silo is opened for feeding silage will start to deteriorate [72]. The size of the silage structure plays an important role in this phase because it is recommended to remove at least the amount of silage per day shown in Table 3 to minimize deterioration

in the face exposed to oxygen. A smooth face is also recommended. Hence, the machinery used plays a key role both during the compaction and the feeding.

Special attention also needs to be paid to effluent losses. Maize, grass and cereal silage produce little effluent, but because of its moisture content, the effluent from beets runs off rapidly [51]. This effluent has a high energy content so it is important to capture it and feed the digester with it [63].

### *4.3 Future work*

#### 4.3.1 Quality Requirements of Silage for AD

More research is necessary to understand the effects of DM losses and a focus on the compensatory relationship between DM losses and methane enhancement. This may improve the crop's methane yield per hectare [34], which is a critical factor for silage productivity, and the sustainability of silage for AD, since land use requirements for crop growth could be reduced. Further investigation and experimentation into optimal chop lengths is also strongly recommended, as suggested in [6] and [62]. Particular emphasis should be on determining the relationship between increased methane yields and increased costs of shorter chop lengths.

#### 4.3.2 Additives for AD

Very little research has been carried out on the development of specific additives for ensiling of biogas feedstock, away from the considerations of animal feed. Specifically, the formulation of additives consisting of complex mixtures of homo and hetero LAB as well as enzymes or bacteria, as suggested by [48] should be considered. Additionally, the use of acidic additives, such as formic and acetic acids, as chemical preservatives should also be explored. To date, these have been largely ignored, since many are inappropriate for animal feed due to decreased carbohydrate preservation and DM losses [15,40]. Yet, some acidic pre-treatments have been shown to improve biogas production as a consequence of cellulosic material breakdown and increasing the accessible surface area of the crop material [15]. Therefore, although such acidic additives are likely to be associated with DM losses, these may be compensated for by improved crop digestibility.

#### 4.3.3 Silage Production and Management Practices

Silage production and management practices are some of the most important factors that may influence energy losses [65]. To date, it is largely considered that the key factors involved in silage destined for AD and animal feed are similar. Yet, it is clearly evident that different silage management practices are likely to be required. Therefore, future research should also concentrate on the investigation of differences in silage production and management practices of farmers with crops destined for AD and animal feed.

One of the key contributors to such expected differences in requirements is due to differences in the type of operations. In addition to the disparities in silo size, the majority of AD farmers (72%) reported using more than one crop when ensiling, whilst only 25% of animal feed farmers employed such practices [60]. Therefore, conditions for mixed silage, in addition to single crop silage, should also be identified, yet these have not been taken into account to date. Of concern is that the majority of farmers in [60] have indicated that they would not consider investing in training in silage management. Yet at the same time, poor silage management was one of the main causes of energy losses during the silage making process, together with bad weather conditions during ensiling [60].

The differences between the key considerations for AD farmers and dairy farmers provide further support to the idea stated in [38] and [34] that the method of quality evaluation should be slightly different than for animal feeding. However, without the necessary data that defines the degree of dependence between quality parameters and methane formation, it is not possible to provide conclusive indications for optimal silage production and management practices for AD.

#### 4.3.4 Silage management for agricultural residue to AD

Energy crops produced for AD have attracted a lot of scientific and societal discussions that relates to competition with feed cropping, food production and environmental efficiency. Thus, ensiling agricultural residues for AD in place of whole crops is now considered to address these controversies and bring about a concomitant nutrient cycle maintenance and the management of residues [2]. Since residues are of varying types or quality and accrue at different locations, amounts and time, ensiling is an essential tool for its preservation and pre-treatment for an improved feedstock quality that is sustainable [2]. Table 4 gives a list of ensiled residues and their sources.

For a successful residue silage production, it is important to note the different physical structure and compositions of the residues to be employed in the process [81]. For instance wilting is an important pre-treatment for high moisture residues like sweet potatoes vines and grass chippings, whilst tightly packed residues like maize stover and cereal straws require slight wetting. Prior to ensiling, pre-treatments, like fine chopping, use of additive and co-digestion are required for residues with low water soluble carbohydrates (WSC) in order to increase their DM. For instance finely chopped cereal straw can be mixed with chopped vines before ensiling [80]. Protein rich feeds such as fish wastes, should be co-ensiled with spent grain or fruit wastes such as watermelon residues which has been reported by [85] to be energy rich.. Also, molasses can be applied as additives to any residue silage treatment to achieve a high quality silage [81].

There are a number of foreseeable challenges with the application of silage residues to AD, since residues are from a broad range of feedstocks that are diverse in composition and structure [2]. In addition, the supply chain is not yet sustainable as residues accrue in small

amounts and are decentralized and their collections may be challenging both logistically and monetarily. Also of concern is that some residues are not readily biodegradable and may contain high levels of toxin or be contaminated with impurities and pathogens [2,86].

**Table 4:** List of ensiled residues and their sources

<b>Residue source</b>	<b>Examples</b>	<b>References</b>
<b>Landscape management</b>	grass clippings, or yard trimmings, pruned branches, shaded tree leaves	[2,77,78]
<b>Crop production</b>	maize stover (that include; stalks, leaves, husks, and cobs), sweet potatoes vines, cassava leaves and cereal straw	[79,80]
<b>Agro-industrial by-products</b>	spent grain, fish wastes, molasses, fruits and vegetable wastes	[81,82]
<b>De-weeding and maintenance of waterways</b>	aquatic plants and algae biomass	[83,84]

## 5 Conclusions

The employment of silage for use in AD is anticipated to keep increasing in the coming years and decades, as increasing efforts to meet renewable energy targets are made. To date, silage for AD is largely treated as silage for animal feed by many operators. However, although the principles of ensiling remain the same, some specific differences do exist e.g. acetic acid could be present in higher levels in silage for AD as it enhances methane formation. Overall, the moisture content, chop length, additive usage, silo type and silo management have been identified to be the factors that have the greatest impact upon methane yields. In particular, conventional additives, except heterolactic bacteria, reduce DM losses but have little effect on methane yield. Crops for AD use should be chopped to shorter lengths and ensiled at a lower dry matter content than the ones for animal feeding. Finally, management is the most important factor influencing DM and energy losses, especially during filling and feed out.

The specific recognition of the differences between the use of silage for AD and crops is of particular importance as it will allow for best-practice in and improve bioenergy production and sustainability.



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## 6 References

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