CRANFIELD UNIVERSITY

LELIA ORTEGA RODRÍGUEZ

DEVELOPMENT OF A BEST PRACTICE GUIDE FOR SILAGE SYSTEMS IN ANAEROBIC DIGESTION

SCHOOL OF APPLIED SCIENCE
Waste and Resource Management

MSc
Academic Year: 2013 - 2014

Supervisor: Raffaella Villa
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

Maximum methane yields in AD processes using silage feedstock can only be achieved with high quality material. This study aimed at collecting and examining the information available on silage making for biogas production through a literature search and an on-line survey. The effect of ensiling on the energy yield was determined, as well as the influence of different parameters on the silage quality such as; characteristics of the crop at ensiling, silo design and silage management. The on-line questionnaire was used to understand the practice of silage making in the UK. The findings of this study suggests that principles of controlling silage preservation for biogas production remain the same that for animal feeding. However, some differences have been shown in the use of additives, optimal moisture content and chop length of the crop at ensiling, sizing the storages systems and evaluating the energy losses. The results of this research were used to develop a farmers' guide to achieve best quality silage for AD and allowed for future research needs to be identified.

Key words: *Biogas, methane yield, dry matter, quality silage, storage systems*

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AD	Anaerobic digestion
CV	Coefficient of variation
DM	Dry matter
LAB	Lactic acid bacteria

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Development of a best practice guide for silage systems in anaerobic digestion (AD)

Ortega Lelia, Villa Raffaella, Fenech Cecilia

Centre for Energy & Resource Technology, Cranfield University, Cranfield, Bedfordshire,MK 430AL, UK

ABSTRACT

Maximum methane yields in AD processes using silage feedstock can only be achieved with high quality material. This study aimed at collecting and examining the information available on silage making for biogas production through a literature search and an on-line survey. The effect of ensiling on the energy yield was determined, as well as the influence of different parameters on the silage quality such as; characteristics of the crop at ensiling, silo design and silage management. The on-line questionnaire was used to understand the practice of silage making in the UK. The findings of this study suggests that principles of controlling silage preservation for biogas production remain the same that for animal feeding. However, some differences have been shown in the use of additives, optimal moisture content and chop length of the crop at ensiling, sizing the storages systems and evaluating the energy losses. The results of this research were used to develop a farmers' guide to achieve best quality silage for AD and allowed for future research needs to be identified.

Key words: *Biogas, methane yield, dry matter, quality silage, storage systems, management*

1 INTRODUCTION

In 2008, European Union policies set a target that 20% of energy must be supplied by renewable sources by 2020 (Erbach, 2014). Consequently, there is a significant increase in biomass cultivation for the purpose of bioenergy, in particular for biogas production via anaerobic digestion. Germany is the largest biogas producer in Europe and it is also the country with the most hectares of land used specifically to grow plants for energy in Europe (Panoutsou et al., 2011).

When crops were only supplied for feed and food, the farmer's objective was to improve the nutritive value of crops. However, for biogas production the objective is different. Rather, it is to achieve the highest possible methane yield (KWS UK Ltd, 2014). The methane yield (m^3CH_4. ha^{-1}) depends upon the feedstock biomethane potential (m^3CH_4. t^{-1}) and the biomass yield (t. ha^{-1}) (Mayer et al., 2014). Both of these parameters can be influenced by various factors throughout the feedstock chain (cultivation, harvest and storage) (Herrmann et al., 2011). Therefore, in order to optimize methane yield, factors that influence feedstock quality should be identified and managed.

Previous studies have reported that the specie selection, the harvest time and the storage process are the most important factors (Mayer et al., 2014; Heiermann et al., 2009). However, while methane formation from different types of biomass and from different harvesting times are relatively well understood, there has been little discussion of the influence of the storage process on methane production so far.

The digesters can be fed both with fresh or ensiled feedstock (Kalač, 2011). Nevertheless, most of the time the feedstock needs to be preserved. This is because while crops accumulate seasonally, biogas plants have to be fed continuously (Prochnow et al., 2009). Ensiling is the preferred procedure to do it because silage can be stored for months or years and energy losses are lower in comparison to other methods (Chin, 2001). Ensiling consists of various biochemical processes and directly or indirectly affects the biogas production by changing the properties of the feedstock (Kalač, 2011). It is known that maximum methane yields can only be achieved with high-quality silage and that some crops, for example energy beet, need more careful storage than others (KWS UK Ltd, 2014).

Silage making is a traditional method of preserving crops for cattle feed. Hence, the technology of forage ensiling for cattle feeding is well developed. However, silage for animals needs to provide minimum methane production in the rumen, and this is the opposite of what it is required for biogas production. Therefore, some quality characteristics or considerations for achieving high quality silage should be different.

The aim of this report is to collect and assess all of the available information on silage making and storage of energy crops in order to develop a guide that allows operators to achieve high-quality silage for use in AD.

2 LITERATURE REVIEW

2.1 Biochemistry of ensiling

There are four phases during silage fermentation: aerobic phase, anaerobic phase, stable phase, and feed-out phase (Sakhawat, 2011) (Figure 1)

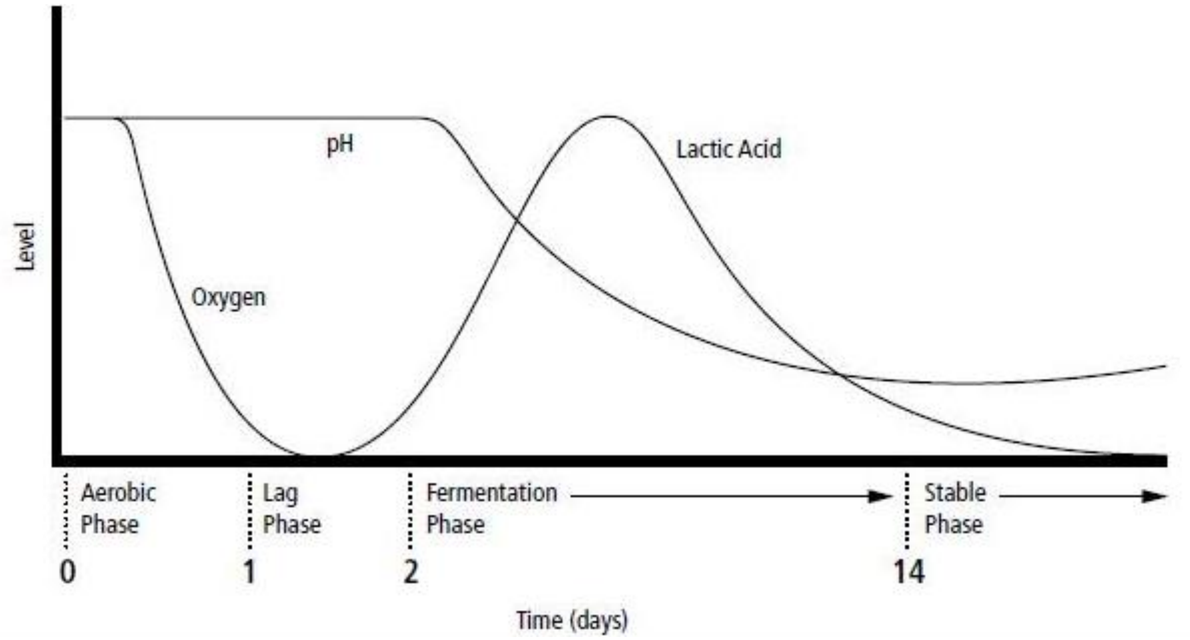

Figure 1. The changes of the essential elements of fermentation over time. Source: Van Soest, 1994

The aerobic phase occurs during the chopping, filling, and packing steps (Lemus, 2010). During this phase, oxygen is eliminated as a result of respiration. Respiration is a wasteful process where aerobic microorganisms consume sugars that are also the main food for lactic acid bacteria and digester microorganisms, because of their high digestibility. Therefore, their respiration causes losses of energy and dry matter (DM) (Sakhawat, 2011).

Once all of the oxygen is eliminated, the anaerobic phase starts. This phase is dominated by growth of lactic acid bacteria (LAB) and sees a pH drop to 3.7–5.0 due to increasing lactic acid concentrations (CHR Hansen, 2005). At this pH-level the growth of harmful microorganisms, mainly enterobacteria, clostridia and yeasts, is inhibited (Sakhawat, 2011).

The stable phase starts when the growth of LAB stops (CHR Hansen, 2005). At this point, the LAB are dominant and lactic acid becomes the predominant endproduct formed. If the silo is properly sealed, DM and energy losses in this phase should be minimal *(Heguy and Silva, 2010).*

The feed-out phase begins when the silo is opened and continues until all the silage has been removed and fed (CHR Hansen, 2005). 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 increase spoilage and hence, reduce silage quality (Heguy and Silva, 2010).

Table 1 shows mass and energy recovery depending on the microorganisms mentioned above. The key to achieve an efficient preservation of the biomass energy content is the combination of the absence of air and the bacterial fermentation of sugar. However, under sub-optimal conditions considerable dry matter and energy losses can occur either during anaerobic conditions (fermentation losses) or due to aerobic deterioration. (McEniry and O'Kiely, 2013).

Table 1 Mass and energy recovery for fermentation during ensiling. Source: Adapted from Kreuger et al., 2011

Pathway	Consume:	Produce:	Mass recovery (%)	Energy recovery (%)
Homofermentive LAB	sugars	lactic acid	100	97
Heterofermentative LAB	sugars	lactic acid+ acetic acid	100	93
	sugars	lactic acid+ ethanol+ CO2	76	97
Enterobacteria[a]	sugars	acetate+ethanol+CO2+H2+H2O	78	83
Yeast[a]	sugar	ethanol+CO2	51	97
Clostridia spores[a]	sugar+lactic acid	butyric acid+CO2+ H2	49	78

[a] *Undesirable pathway*

2.2 Effects of ensiling in methane formation

The impact of ensiling on methane formation, and consequently energy recovery, has been studied for different crop species in recent years. This literature review is mainly focused on four energy crops: maize, grass, whole crop cereals and beet, which are the dominating energy crops used in the UK according to the biogas in practice guide (KWS UK Ltd, 2014). *Table 2* shows the impact of ensiling energy crops without additives on methane production found in the literature.

Table 2 Impact of ensiling without additives on methane formation.

Crop	Storage duration	Methane potential m3 CH4 .kg-1 VS added Fresh	Silage	Change (%)	Ref
Maize	44 days	0.383	0.338	-12	Neureiter et al., 2005
Maize	119 days	0.383	0.48	25	Neureiter et al., 2005
Grasses	3 months	0.23	0.18	-22	Lehtomäki, 2006
Beets tops	3 months	0.31	0.23	-26	Lehtomäki, 2006
Grasses	6 months	0.23	0.18	-22	Lehtomäki, 2006
Beets tops	6 months	0.31	0.43	39	Lehtomäki, 2006
Maize	n.r [c]	0.225	0.289	28	Amon et al., 2007
Grasses	3 months	0.41	0.42	2	Pakarinen et al., 2008
Grasses	12 months	0.41	0.48	17	Pakarinen et al., 2008
Rye grass	3 months	0.48	0.39	-19	Pakarinen et al., 2008
Rye grass	12 months	0.48	0.37	-23	Pakarinen et al., 2008
Barley [a]	3 months	0.438	0.462	5	Heiermann et al., 2009
Rye [a]	3 months	0.37	0.476	29	Heiermann et al., 2009
Triticale [a]	3 months	0.534	0.555	4	Heiermann et al., 2009
Sugar beet	<6 months	0.377	0.407	8	Weissbach, 2009
Sugar beet	> 6 months	0.377	0.437	16	Weissbach, 2009
Maize	3 months	0.329	0.359	9	Herrmann et al., 2011
Maize	12 months	0.329	0.378	15	Herrmann et al., 2011
Sorghum [b]	3 months	0.317	0.327	3	Herrmann et al., 2011
Sorghum [b]	12months	0.317	0.345	9	Herrmann et al., 2011
Rye [a]	3 months	0.293	0.333	14	Herrmann et al., 2011
Rye [a]	12 months	0.293	0.343	17	Herrmann et al., 2011
Triticale [a]	3 months	0.339	0.364	7	Herrmann et al., 2011
Triticale [a]	12 months	0.339	0.353	4	Herrmann et al., 2011
Maize	n.r [c]	0.353	0.357	1	Kreuger et al., 2011
Beets	n.r [c]	0.447	0.405	-9	Kreuger et al., 2011
Beets tops	n.r [c]	0.437	0.357	-18	Kreuger et al., 2011
Maize	6 months	0.344	0.128	-63	Chen et al., 2013

[a] Whole crop cereals [b] Grass [c] No reported

Ensiling has been reported to increase methane yields up to 11% by Herrmann (2011). In the same vein, more authors noted that ensiled material showed higher methane content than fresh matter based on volatile solids (VS) (Neureiter et al., 2005; Amon et al., 2007; Pakarinen et al., 2008; Weissbach, 2009; Heiermann et al., 2009). The reason for such an increase in methane content is not yet certain. However, this could be explained by the increase of organic acids and alcohol during ensiling (Herrmann et al., 2011)

In contrast, Chen et al.(2013) found that there is no significant difference in methane yields between ensiled and fresh crops. Similarly, Kreuger et al.(2011) reported that ensiling does not increase the methane yield. In addition, it was determined that the apparent methane yield growth reported in most of the studies mentioned above (Neureiter et al., 2005; Amon et al., 2007; Herrmann et al., 2011; Pakarinen et al., 2008) is due to an analytical error in the estimation of the methane yield. They are based on procedures of VS determination without correction for the loss of volatile compounds, which would cause an overestimation of the methane yield per unit of VS. Therefore, the fact that some published methane yields are based on uncorrected VS needs to be highlighted and the results need to be regarded with caution.

Despite this analytical error in a majority of the papers, it should be noted that Weissbach (2009), based on corrected VS, remarks that the methane potential of ensiled crops is higher than that of fresh crops. A more recent study by McEniry and O'Kiely (2013) also reported that some fermentation products have the potential to enhance methane yield, especially the ones that are the result of undesirable microbial activity. Ohl et al. (2012) also found that poor silages reach higher methane potentials caused by the high yields of fermentation acids. However, methane yield ($m^3CH_4. ha^{-1}$) does not only depend on methane potential, it also consists of the biomass yield ($t. ha^{-1}$) (Mayer et al., 2014) and both McEniry and O'Kiely (2013) and Ohl et al. (2012) point out that the enhanced methane potential reported in most of the studies may not compensate for the associated DM and energy losses occurring during ensiling. This is because these fermentation products are the result of undesirable microbial activity (see Table 1).

Some research has also been carried out on the effect of adding additives during the ensiling process on the final methane production. This will be explained in more detail in section 2.4.3.

Weissbach (2009) assessed how the methane potential varies depending on the crop ensiled. It was observed that fresh beets have less biogas potential than other cereal and forages. After ensiling, beets were observed to not only have better biogas potential than the other crops, but also that the methane content of biogas was higher due to the increasing ethanol formation that takes place during the fermentation.

The effect of storage time on methane yields has been studied by Herrmann et al. (2011), Weissbach (2009) and Neureiter et al. (2005) (Table 2). All three reported that longer storage periods have a positive effect on methane yield. This could be because, in well preserved silage, the concentration of ethanol increases as a function of the age of silage (Weissbach, 2009).

2.3 What is good quality silage for AD?

Silage quality is usually considered as a precondition for high methane yields in AD (Prochnow et al., 2009) (Kalač, 2011). However, Mrůzek and Groda (2011) state that storage requirements may be not as stringent as when used for animal feeding. This is because some factors of importance in animal nutrition (protein content, digestibility, palatability or DM intake) have little consequence in AD, where preservation of energy during storage is the main concern ((Egg et al., 1993)

Egg et al.(1993) state that ensiling has been shown to conserve 93% of the crops gross energy when good practices are followed. On the other hand, poor silage management practices in all phases have been associated with energy losses as high as 40% (Egg et al., 1993). Prochnow et al. (2009) notes that some experiments prove an unusual reduction of biogas yields due to aerobic deterioration of silage. According to Ploechl et al. (2009) , the principles of ensiling to produce biogas or for animal feeding remain the same; high lactic acid, low pH, prevention of clostridia and enterobacter growth and the prevention of silage losses and aerobic stability after opening the silo. *Table 3* shows the silage fermentation profile recommended by previous researchers to obtain proper preservation of maize, grass, whole crop cereal or beet.

Table 3 Target value of fermentation characteristics

Parameter	Target value: Maize (Chahine et al., 2009)	Grass (Nizami et al., 2009)	Whole crop cereal (Kaplan et al., 2014)	Beet (Norell et al., 2007)	Reasoning (Chahine et al., 2009)
pH	<4.2	<4.5	<4.2	<4	The pH will be lower for wetter silages. The more efficient the pH decline, the more water soluble carbohydrates will be conserved in the silage mass
Lactic acid (g/kg DM)	40-70	80-120	30-60	>30	The more lactic acid the better. Higher levels indicate good fermentation and better preservation. Lower levels indicate the silage was not harvested at the proper moisture content, incorrect chop length, not well packed or exposition to oxygen.
Acetic acid (g/kg DM)	10-30	20-50	10-30	<15	High levels may indicate the silage was not packed densely or quickly enough, was not covered appropriately or was too dry. Actic acid increase aerobic stability, therefore some additives (hetero LAB) also produce it.
Butyric acid (g/kg DM)	<1.3	<10	<3	<0.2	High levels indicate clostridia fermentation, which means high energy losses (see table 1)

Despite the principles of ensiling remaining the same, when considering silage for biogas production it is important to compare methane yield per hectare as well, because DM losses due to the formation of some organic acids may be compensated by improving crop digestibility (Ploechl et al., 2009). For example, acetic acid is inappropriate for animal feed, but might be positive for biogas production since it enhances methane formation. Therefore, further study is necessary to understand the degree of dependence between well preserved silage and methane yield (Idler et al., 2007).

2.4 Factors to obtain the highest quality silage

The primary objective in preserving crops for biogas production is to prevent energy losses during storage (Egg et al., 1993; Kalač, 2011). The amount of losses and the final silage quality are influenced by a number of factors: (1) moisture (2) and chop length of the feedstock, (3) the use of additives, (4) storage system and (5) silo management.

2.4.1 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 (Lehtomäki, 2006).

It could be said that moist material is preferred for the degradation in the digester (Lehtomäki, 2006). When harvested crop, like grass, has a higher moisture content than is desirable, the cut material is left in the field in order for it to wilt. *Table 4* shows the DM values found in the literature for crops for biogas production and their comparison with crops for animal nutrition. Lower dry matter levels will increase leachate, which is associated with significant energy losses (KWS UK Ltd, 2014). On the other hand, higher dry matter levels reduce methane yields because the silage is more difficult to degrade. Moreover, silage cannot be optimally compacted, which has a negative impact in storage stability (Gülzow, 2012).

Table 4 DM content range of selected energy crops

Energy crop	DM range (%)	Range for animal feeding (%)
Maize	27-31 (KWS UK Ltd, 2014)	30-35 (KWS UK Ltd, 2014)
Grass	26-30 (Prochnow et al., 2009)	30-45 (DOW, 2008)
Whole crop cereal	30-36 (GrainSeed Ltd., 2014)	33-50 (Mickan, 2008)
Beet	20-23 (Gülzow, 2012; omafra, 2013)	25 (omafra, 2013; Gülzow, 2012)

2.4.2 Chop length

Short lengths are beneficial for preservation because they enhance compaction and oxygen elimination in the silage. For cattle feeding, particle size needs to be long enough to float in the rumen and maintain the rumen fibre. If not, digestive disorders can be caused in the animals (Barnhill et al., 2009). However, for biogas production a shorter length has a positive effect on the silage degradability in the digester. Shorter lengths offer a larger area for the bacteria to break down the crop and produce gas more easily *(*Carley, 2013). Hence, this may result in the shortening of retention times required within the AD. Furthermore, Herrmann et al. (2012), reported that shortening the chopping length increased lactic acid fermentation during ensiling and enhanced methane yield (*Figure 2*)

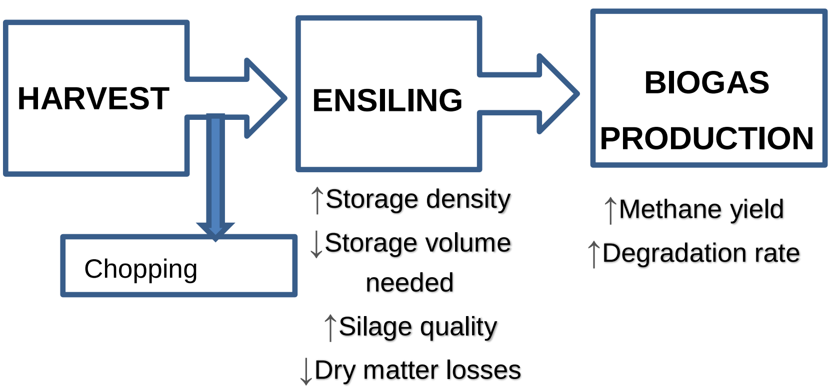

Figure 2 Chopping length in the biogas chain Source: Adapted Herrmann et al., 2012

Therefore, silage for biogas production should be chopped to shorter lengths than the one for cattle feeding. The optimal chop length will vary depending on the crop ensiled (*Table 5*). Herrmann et al. (2011) studied the effect of chopping length in silage quality for biogas production. It was concluded that a cutting length of 7-8 mm is the optimal cutting length for maize and that chopping to shorter sizes will not improve the overall process economy.

In the case of grass, Prochnow et al., (2009) stresses in an article about bioenergy from grassland, that the chopping of grass has provided a range of different responses. For example, an experiment in a farm in Finland chopped grass to 5, 10 and 20 mm and the grass silage yielded most methane at the 10 mm size. On the other hand, experiments in Germany with grass silage demonstrated that increasing methane yields were obtained with the shorter chopping (4mm).

With cereals, such as Rye or Triticale, a chop length of 12 millimetres or less is advisable to maximise methane production (GrainSeed Ltd., 2014). In the case of sugar beets, some studies (Wagner et al., 2011; Elsoms, 2014) consider that the best way is to ensile the whole beet and chop it before it is fed into the digester. This is probably because of the fact that chopped beets produce significantly more effluent than whole beets and the risk of nutrient losses through uncontrolled effluent is notably increased (Wagner et al., 2011)

Table 5 Chopping length range of selected energy crops

Energy crop	Chop length range (mm)	Range for animal feeding (mm)
Maize	7-10 (KWS UK Ltd, 2014); (Herrmann et al., 2011)	12-15 (KWS UK Ltd, 2014)
Grass	4-10 (Prochnow et al., 2009); (DLG, 2012)	10-25 (BGS, 2007)
Whole crop cereal	7-12 (GrainSeed Ltd., 2014); (Elsoms, 2014)	20-50 (Mickan, 2008)
Beet	-[a]	

[a] Whole beet ensiled

2.4.3 Additives

In field conditions, adequate fermentation conditions are not always guarantied and that is why additives are used. Their application may help to affect the preservation process in several ways (Kalač, 2011):

- Chemical preservatives (e.g. formic acid): suppress undesirable microbiota, as Clostridia.
- Lactic acid bacteria (LAB): help to accelerate lactic acid fermentation.
- Molasses: increases fermentable carbohydrates

These additives (except hetero LAB) reduce DM losses during ensiling but they do not have significant effect on methane production (Banks, 2004; Neureiter et al., 2005; Pakarinen et al., 2008; Herrmann et al., 2011).This makes sense, because in contrast with biogas production, for animal feeding, the minimum formation of methane in the rumen is desirable. Only hetero LAB have a positive effect on methane yield because of the acetic acid and ethanol (Vervaeren et al., 2010; Idler et al., 2007b). As mentioned in section 2.2, there is a relationship between organic acids (lactic acid, acetic acid, propionic acid, butyric acid) and methane yield. Therefore, a good additive for energy crops should enhance their presence and, at the same time, accomplish the first objective of storage loss minimisation (Ploechl et al., 2009). Vervaeren et al. (2010) reported that a more complex additive with homo and hetero LAB as well as enzymes or bacteria may be the most appropriate for this objective.

2.4.4 Storage system

There are several types of silo in use. Silage clamps, silage bags and wrapped bales are the most commonly used storage systems (*Figure 3*). Good quality silage can be obtained by using any of the storage systems, as long as the design and management of the silo is appropriate. However, according to Kaiser et al. (2004), ensiling beet in bales risks poor fermentation and an increase in DM losses because of its moisture content

Figure 3 Silo structure types. From left to right: Bunker or silage clamp, field clamp, bagged silo and wrapped bale. Source: www.google.com

Table 6 shows a comparison of silo constructions considering different factors. Types of clamps range from the walled clamp (bunker) to a simple stack (field clamp). Bunker or clamp silos consist of a permanent structure constructed above ground with three walls. The walls are usually made of concrete, steel or railway sleepers (Kaiser et al., 2004) and floors used to be made of concrete with drainage channels to facilitate the collection of effluent.

The wall slope and height will affect packing ability, therefore, clamp design plays an important role in silage making. Sloped walls have been proved to facilitate consolidation (Hartley, 2014) as well as high walls (ACP(concrete) Ltd., 2013). Another critical element that needs to be determined in the clamp design is the exposed face. By reducing the exposed face area clamp losses are minimized, hence, clamps should be sized to match the recommended feeding rates shown in *Table 7* (Muck, 2006)

The inexpensive alternative to bunker or clamp silos 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 (Kaiser et al., 2004). 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 (Norell et al., 2007).

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 (Bernardes and Chizzotti, 2012). Various experiments prove that ensiling in bags results in low dry matter losses due to the rapid exclusion of air (Norell et al., 2007). In small scale plants the use of wrapped bales can be a good alternative because of its suitability for small batches (Hopwood, 2011). However, even though high quality silage can be made with wrapped bales, fermentation is somewhat restricted relative to fermentation in other silo types (Muck, 2006). The main disadvantage of both systems is the high storage cost per ton of silage *(Kaiser et al., 2004).* However, the development of these systems is ongoing, in order to help them produce more consistent silage and to make them more efficient (Bernardes and Chizzotti, 2012).

Table 6 Comparison of silo structure types. Source: Adapted from (Kaiser et al., 2004; Fyksen, 2006)

Criteria	**Bunker/ Clamp**	**Pile/ Field clamp**	**Bagged**	**Baled and wrapped**
Construction cost	High	Low	Low	Low
Cost/ tonne of storage DM	Low	Low	High	High
Flexibility and capacity	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
Footprint	The smallest	Larger than in bunkers	Larger than bunker and pile	The largest
Durability	Long lasting	Better for short storage periods	Not suitable for storage > 3 years	Not suitable for storage > 12 months
Suitable crops	All crops	All crops	All crops	Not suitable for high moisture crops
Machinery required	Conventional farm equipment	Conventional farm equipment	Specialized equipment	Conventional farm equipment
Compaction achieved	Good (better with slanted wall)	Lower density than bunkers	Adequate, but lower than bunkers	Adequate
DM losses expected	Higher than bags	The highest	The lowest	Higher than bags
Labour requirements for filling	More than for bags and bales	More than for bags and bales	Modest	The least
Expose surface face at feeding	Large	The largest	The smallest	Small
Management issues	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)

2.4.5 Silo management

Most of the subject matter surrounding the management of silos considers that the key factors involved are similar to those involved with the management of animal feeding. 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 (see *Table 7*).

Table 7 Silo management practices to minimize energy losses depending on the silo structure

		Clamp/bunker silo	Field clamp	Ag-Bag	Big bale
Filling (Jones, 2004)		Chop at correct length Optimal DM Rapid fill Progressive wedge technique	Chop at correct length Optimal DM Rapid fill Progressive wedge technique	Chop at correct length Optimal DM Rapid fill	Optimal DM
Compaction (Jones, 2004)		Compress with tractor during filling	Compress mechanically during filling	Set filling machine for high compaction	Bale tightly
Sealing (Jones, 2004)		Immediately after filling Cover with plastic seal ends and sides carefully	Immediately after filling Cover with plastic seal ends and sides carefully	While it is filled Seal ends carefully	Immediately after baling Wrap or seal carefully
Storage (Jones, 2004)		Check every two weeks Seal cracks in wall, repair holes in plastic cover	Check every two weeks Repair holes in plastic cover	Check every two weeks Repair damaged bags	Check every two weeks Repair damaged bags
Feed out (Muck, 2000)	Winter	10 cm/day	10 cm/day	10 cm/day	
	Summer	16cm/day	16cm/day	16cm/day	

Filling and compaction: Prior to filling, it will be essential to clean the ground or floor to prevent contamination (KWS UK Ltd, 2014). Dirt contamination can present problems to all crops because of the Clostridia present in it, especially with beet silage (Kaiser et al., 2004) . Irrespective of the type of storage system the plant material must be compacted as densely as possible. Filling the silo at the recommended dry matter content and chop length to enhance good compaction and do not allow the ingress of air. The expected densities when ensiling at optimal conditions are shown in *Table 8*.The silo structure should be filled quickly. In large clamps, where the filling requires several days, the material should be compacted with the progressive wedge technique. In this way the currently day material will be 'sealed' by the next day material minimising aerobic deterioration (Moran, 2005).

Table 8 Compaction expected at optimal dry matter content

Crop	DM (%)	Density (kg/m^3)
Maize	27-31	230 (Schaumann Bioenergy, 2013)
Grass	26-30	210 (DLG, 2012)
Whole-crop cereal	30-36	230 (KWS UK Ltd, 2014)
Beet	20-23	-*

*No data found

Sealing: Well-sealed storages help to minimise aerobic losses during storage (Moran, 2005). In clamps, how well the silo is sealed depends on the plastic used and how it is held in place. The standard material used in the sealing system is the polyethylene film. However, recent studies on oxygen barrier films (Berger and Bolsen, 2006; Borreani et al., 2007) found that silage sealed with oxygen barrier film have significantly less DM losses in comparison with the same silage covered with polyethylene. Similarly, Orosz et al. (2013) proved that the oxygen barrier film is a better inhibitor of the microorganism responsible for aerobic deterioration.

Feeding out: As soon as the silo is opened for feeding, the silage will start to deteriorate (Moran, 2005). 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 7 to minimize the 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 should produce little effluent, but because of its moisture content, the effluent from beets runs off rapidly Norell et al. (2007). This effluent has a high energy content so it is important to capture it and feed the digester with it (Wagner et al., 2011).

3 METHODOLOGY

The three purposes of this section are to (1) describe the research methodology of this thesis (2) describe the procedure used in designing the questionnaire, as well as the system used in collecting the data, and (3) provide an explanation of the statistical methods used to analyse the data.

3.1 Research methodology

The first step of the methodology was to collate the information available from the literature. Since the amount of information available on silage for AD was still limited, it was also planned to collect data from farmers to have a better understanding of 'real life' silage making in the UK. It was agreed with the sponsor, Bock UK (a silage clamp specialist), that the most appropriate way of data collection was a questionnaire. The data retrieved by the literature review, in addition to the information obtained from the survey, will form the guidance document for operators using silage for biogas production (Figure 4).

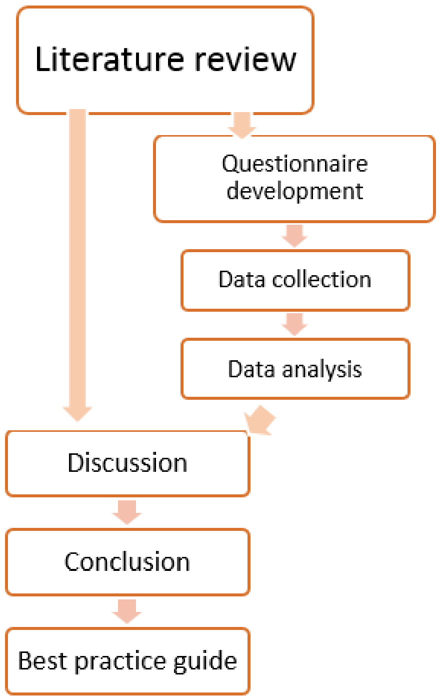

Figure 4 Research methodology

A survey is a research method for collecting information from selected individuals using questionnaires or interviews (The Pennsylvania State University,2006). An online questionnaire was considered to be the more convenient tool for this research since online questionnaires have been shown to be highly efficient at providing information in a short period of time (Cummings et al., 2014). Moreover, they are easier to administrate and less expensive than personal interviews (Cummings et al., 2014)

In order to access as large a sample population as possible, instead of mailing the survey to a selected sample of farmers, the survey link was posted on different internet media (Twitter, UK farming forums, renewable energy webpages).

3.2 Questionnaire development and data collection

Based on the literature research a questionnaire was developed. The questionnaire covered the following topics: crops used, characteristics of the crops at moment of ensiling, design of the silos currently used in the sector (type of silo, age, dimensions) and the main challenges faced by the farmers (where the main losses come from, what they would do differently) amongst others. These topics were asked in order to collate new information to compare or add to that available in the literature. Questions about silo management (filling, compaction...) were not asked because, since it remains the same as for conventional silage in that the subject has been well covered in the literature.

The questionnaire was reviewed by Bock UK and modified after their feedback. The final questionnaire included 29 questions. However, some of the questions were only asked to participants who answered certain options in certain questions. A paper form of the questionnaire can be found in Appendix A.

Some questions were close-ended and others open-ended. Most of the questions were close-ended in order to make the survey easier to answer for the participants and to make the analysis and interpretation of the responses easier as well (Thayer-Hart, 2010). However, some open-ended questions were also added to expand the knowledge in the topic, such as *'what is the biggest issue with your silage which you face every year?'*, since unexpected answers may come out and the farmer's view can be described more accurately (Thayer-Hart, 2010).

Qualtrics (online survey service, version 57,397) was used to complete the questionnaire and data collection. The questionnaire was available during the months of July and August 2014. There was no predetermined minimum response rate, but on this theme, it was considered that receiving a high number of responses enhances the strength of a survey through the ability to draw statistically significant conclusions.

As this study used human participants, certain issues were addressed in order to ensure the privacy and security of the participants. To this end, participants were given an informed consent before starting the questionnaire and the confidentiality of all participants was guaranteed.

3.3 Data analysis

Incomplete questionnaires were not discarded from the analysis so as to not reduce statistical power (because of lower n) and use all the information collected. Therefore, data analysis for each question has been done with the total number of respondents for that specific question.

Numerical data were analysed using statistical equations. The mean, standard deviation and coefficient of variation (CV) have been used to evaluate the variability of the data. Tables and charts were constructed to show the results.

Categorical data need a different way of analysing survey results (Explorable, 2014). The qualitative data from close-ended questions were analysed by identifying the percentage of responses per category and dependence between some qualitative categories were compared by using the Pearson χ^2. Similar comments from open-ended questions were grouped together in order to give a sense of the most frequent ideas.

4 RESULTS

This section shows the results of the survey. Only the most significant results for this research are described. However, data from all the questions and calculations of the data analysis are shown in Appendix B. This will be followed by a discussion of the data collected when set against the literature.

4.1 Response rate

Forty four questionnaires were answered by farmers based in the UK and the dropout rate was 43%. This means that only 25 surveys were completed. Participants who answered less than 10% of the questions were then excluded from analysis. The remaining incomplete questionnaires were taken into account in order to not lose valuable information. Therefore, 40 questionnaires were considered as part in this study

It is important to point out that the number of responses in some questions is much less than the number of surveys submitted. This is not only because of the high dropout rate, but also because in completed questionnaires some farmers left some questions blank. Furthermore, each respondent only saw a selection of all the questions within the survey, depending on their answers to previous questions.

Respondents were segmented into two groups according to the final use of the silage: 'Dairy farmers' (silage for cattle feeding) and 'AD farmers' (silage for biogas production). Dairy farmers represented 70% of the respondents (n=28), while AD farmers represented the remaining 30% (n=12)

4.2 Crops for silage production

Farm volume varied from 100 to 50,000 tonnes of silage per year. Interestingly, there is a huge difference between AD and dairy farmers who filled out the questionnaire. On average AD farmers made 22,333 tonnes/ year (Coefficient of variation (CV) =86%) while dairy farmers only made 1,423 tonnes/year (CV=108%).

72% of the AD farmers reported that they use more than one crop when ensiling, whereas only 25% of the conventional farmers did it. Results regarding the crops used are shown in Figure 5. Grass was the crop most widely cited by both groups of farmers, follow by maize, grass, and finally, beet. The Pearson correlation coefficient between the crop ensiled and the use of the silage shows a positive relationship. This means that the crop selection depends on the final use of it. However, due to the small number of participants, this fact is not statistically significant. Moving on from this, 41% of the AD farmers mentioned that they mix the silage crop with other feedstock, mainly animal waste, when feeding the digester.

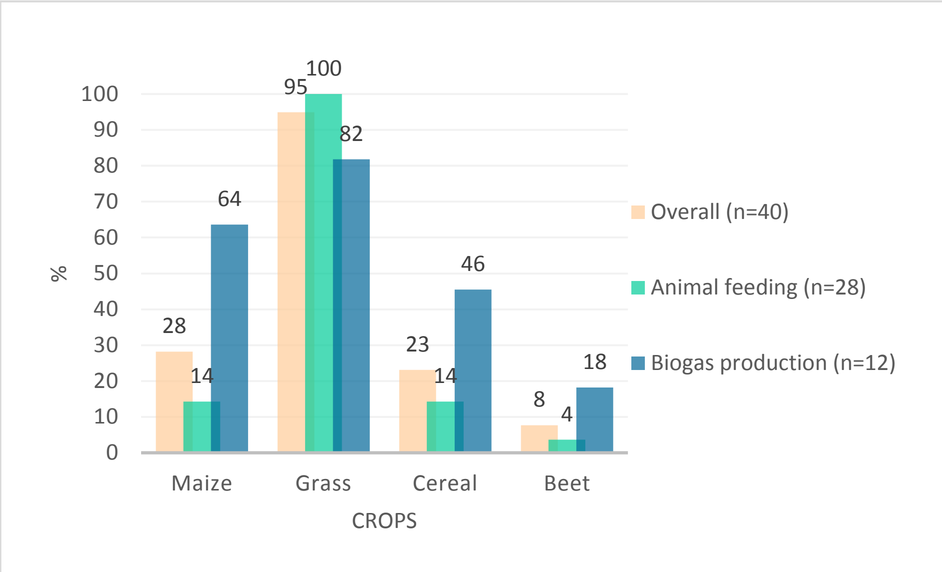

Figure 5 Crops for silage production on UK farms

4.3 Ensiling process

Characteristics (moisture and particle size) of the crops at ensiling are shown in Table 9. It is noteworthy that on the subject of DM content at ensiling, the variance between farmer's responses is relatively small. There is no standard value for chop length. There is a huge coefficient of variance (CV) between answers. For example, for grass (n=20), the particle size reported by farmers ranges from 7 to 250 mm.

Table 9 Chop length and DM content of crops at ensiling on UK farms

	DM content (%)			***Chop length (mm)***		
	Overall	Group		Overall	Group	
Crop		Dairy farmers	AD farmers		Dairy farmers	AD farmers
Maize (n=5)						
Average	31.8	35.0	31.0	8.0	7.0	8.3
CV (%)	2.5	0.0	6.8	15.3	0.0	15.0
Grass (n=20)						
Average	30.2	30.7	27.7	47.6	57.3	18.4
CV(%)	23.4	22.3	27.4	123.0	111.0	87.3
Cereal (n=5)						
Average	31.0	30.0	31.7	22.0	22.5	21.7
CV (%)	9.2	33.3	26.8	70.9	11.1	92.5
Beet (n=1)						
Average	15.0	-	15.0	5.0	-	5.0
CV(%)	0.0	-	0.0	0.0	-	0.0

Only 25 % of respondents commented that they apply an additive when ensiling the crops. This percentage corresponds to the group of dairy farmers, whereas none of the AD farmers reported the use of additives.

The majority of the UK farmers have a bunker silo on their farms (71.0%, n=28), 8.8 % (n=5) use flan pads, 38.6% (n=22) have bales and only 3.5% (n=2) use pressed bag. Some of the farmers (37.5%, n=15) use more than one silo system at once. The group of AD farmers mainly have bunker silos (91.7%, n=11) and dairy farmers, bales (75%, n=28) (See Figure 6). Despite is not statistically significant, the Pearson correlation coefficient between the storage system and the group of farmers shows a positive relationship.

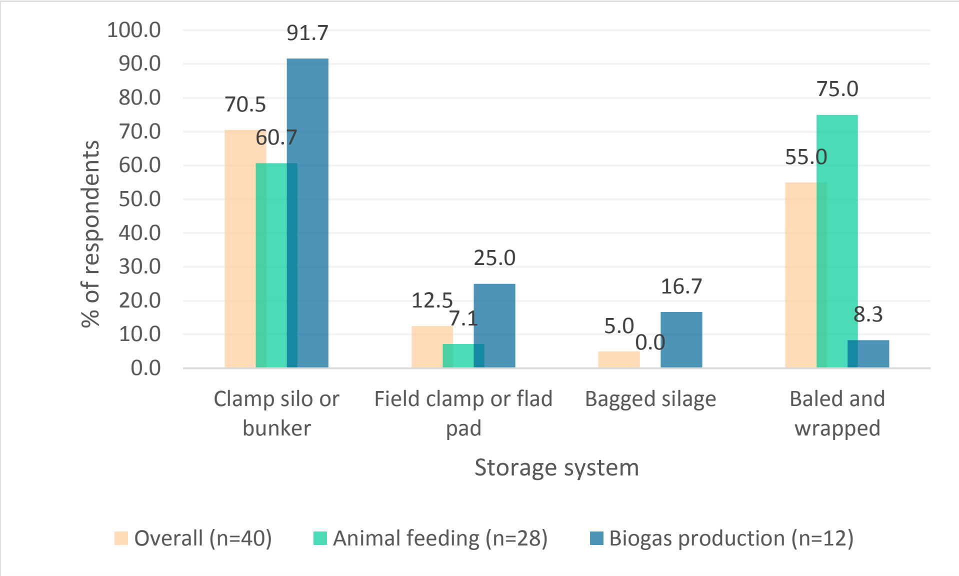

Figure 6 Silage storage system on UK farms

Only 17 farmers, from the 28 that use bunkers, answered the specific questions for clamps. Forty-one percent of them (n=7) have a slanted wall clamp and 59% of them (n=10) have a vertical wall clamp.

In response to questions about clamp manufacturing and installation, 52.9% (n=9) of the farmers reported that they installed the clamp by themselves, without any specialist assistance from a company. This 52.9% corresponds with the farmers that reported smaller clamp dimensions.

In bunker silos, as explained in the literature review, the quality of cover is important. The majority of farmers who answer the two questions about covers use black polyethylene film (88.5%, n=15). 29.4% (n=5) use oxygen barriers, most of them in combination with black polyethylene film. Only 5.9% (n=1) use white polyethylene film. The number of layers used varied between one and three, but two layers is what was stated by the majority of the farmers.

4.4 Barriers and challenges reported by farmers

Farmers were asked to choose the two most important quality parameters for them. As Figure 7 shows, for AD farmers the most important are DM and methane yield. For dairy farmers DM is also one of the chosen options but the other is digestibility.

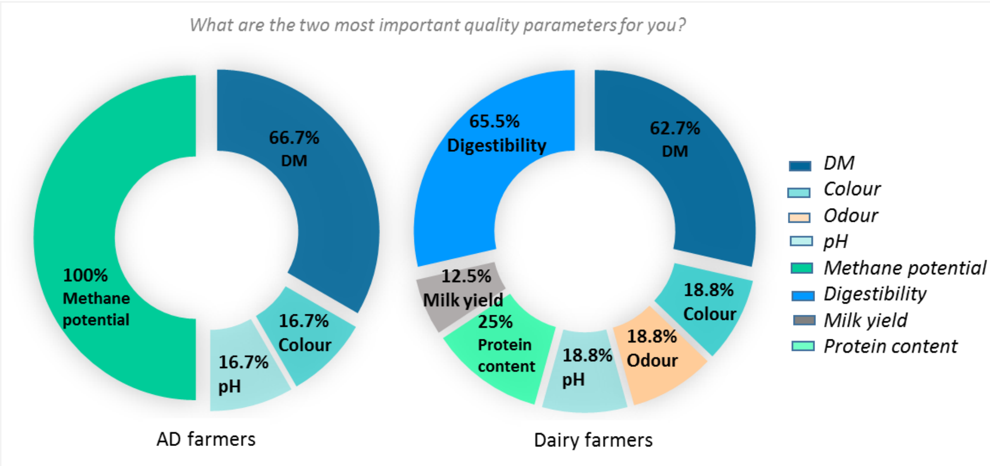

Figure 7 Quality parameters of importance according with farmer's opinion

Figure 8 shows the farmers' opinion about what may be the main cause of energy. As can be seen, they reported bad weather conditions and mistakes during ensiling process (poor silage management) as main causes of losses. On the other hand, incorrect design of the storage system has been reported to not to be an important factor causing losses.

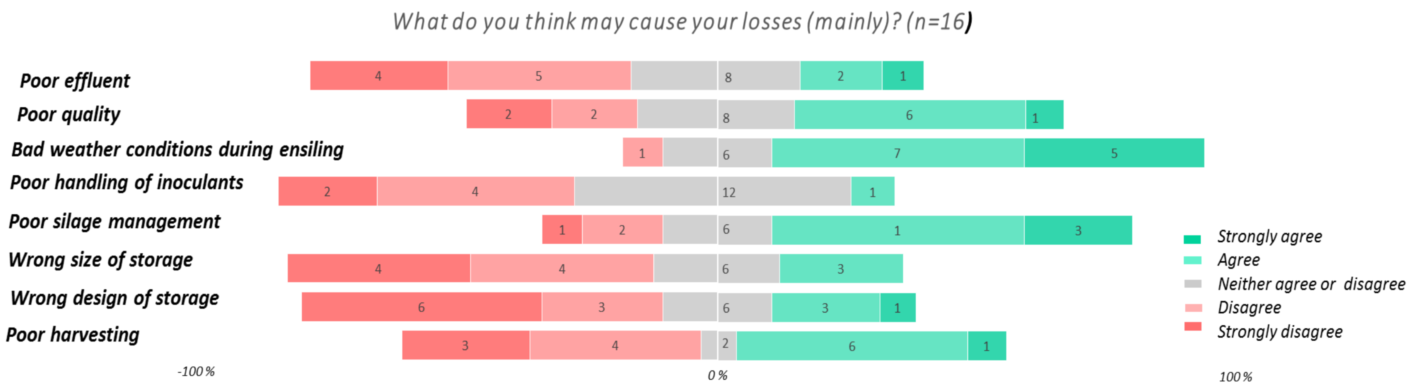

Figure 8 What may cause silage losses mainly according with farmer's opinion

Farmers were asked about the main issues they face every year regarding silage quality. Several aspects were reported, but the one with highest frequency was the need to dry the silage due to weather conditions. In addition, some of the farmers who use bales pointed out their physical handling as the main concern. In relation to the farmers who use clamps, the face of the clamp overheating was mentioned as a problem.

It was found that for the farmers who answered the questionnaire, the increase of yields by avoiding losses is the main question of importance when making silage. Most of them also noted the following as important points; the labour time saving, ease of use regarding covers, a safe working environment and a quick return on investment (*Figure 9*).

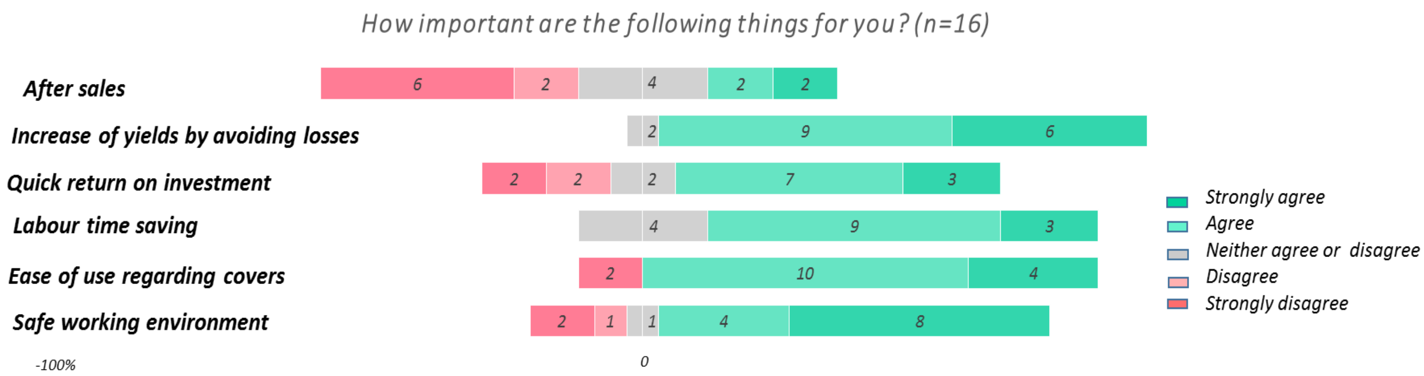

Figure 9 Points of importance when making silage according to farmer's opinion

When referring to the improvements they would make in their storage systems if they could start from starch, thinner clamps was the change most commonly indicated. Some of them would consider building long narrow clamps and others would just install dividing walls in the existing ones. Other changes mentioned by the respondents were better or modern machinery (for better compaction of the silage and for making the clamp easier to fill) and amendment of the water management systems (run off and leachate).

The majority of the farmers (70.5% n=15) are not thinking about buying a new storage system. Similarly, the majority of the respondents would not invest in training on modern silage management, if any.

5 DISCUSSION

This section provides: (1) a critical discussion of the key questionnaire findings (2) a critical discussion of the limitations of this research and (3) suggestions for the future research.

5.1 Survey results

This section provides a discussion of the 10 key findings of the questionnaire results and their relation with the existing literature in order to define whether these findings contribute, support or contradict the existing information.

***1**. The survey data show that maize, grass, whole crop cereal and beet are the main energy crops used in the UK and grass is the most commonly used.*

These four energy crops match those considered for the literature review. Generally, maize is the preferred crop cultivated for AD because of its high methane yield, its agricultural practices are well-known and it is easy to cultivate (Heiermann et al., 2009b). However, the fact that grass was the most mentioned energy crop by farmers, shows that maize is not the only focus of biogas production in the UK. This is in accord with earlier studies which show that plants are increasingly being operated using grass, whole crop cereal and beet as feedstock (ADBA et al., 2011).

2. *The data show that AD farms are much larger than conventional farms.*

Literature does not reflect this difference between the sizes of an AD and a conventional farm. The difference is due to two reasons: firstly, cattle in the UK will only eat silage during the winter, when they are kept indoors, while AD plants will use silage all year round. Secondly, AD plants are much larger and require much more silage per day than the cattle. This not only influences the hectares required for growing the biogas feedstock, also the way of storing silage, since storage system for AD need to be larger.

3. *The data show differences between AD farmers and dairy farmers regarding key considerations in the silage making process*

The question about quality parameters allows for an understanding of what the farmers' key considerations are in the silage making process. The differences between the key considerations for AD farmers and dairy farmers provide further support to the idea stated by Egg et al., (1993) and Ploechl et al., (2009) that the method of quality evaluation should be slightly different than for animal feeding (see section 2.3). However, without laboratory work that defines the degree of dependence between quality parameters and methane formation, it is not possible to recommend exact values at the present time

4. *The data indicate that there is no standard chopping length among AD farmers.*

As noted in the literature review, DM should be lower and chopping lengths should be shorter for AD silage than for conventional silage. These values are advisable for biological and technical reasons (see section 2.4.1 and 2.4.2). The survey data gives an insight of whether farmers' current approach to these two parameters match current knowledge in this regard.

A low standard deviation was present in the results for moisture content of the crops in both groups of farmers. Furthermore, they are consistent with the values reported in *Table 4*. However, a high standard deviation was present for chop lengths. This indicates that, despite some data supporting the optimal values reported in *Table 5*, others are much higher. A possible explanation for this might be that some farmers still remain uninformed about the implications of shorter chop lengths. Another possible explanation is that farmers do not want to assume the additional expenditures from the additional energy demand that shorter cuts involve. The latter would support the ideas of Prochnow et al. (2009) and Herrmann et al. (2012) , who suggested that it is not clear yet if the additional benefit for methane yield exceeds the additional cost.

5. *The data show none of the AD farmers are applying additives.*

An explanation for this finding might be the doubts about their cost effectiveness. According to Ploechl et al., (2009), in many cases the additional increase of methane production could be not compensated by the cost of additive application.

However, due to the large impact that aerobic spoilage due to the growth of yeast has on feedstock costs for AD (Korres et al., 2013), the application of Hetero LAB could be advisable when there is a risk of this kind of deterioration. Hetero LAB is the only conventional additive that reduces energy losses during ensiling and the only conventional additive that has a significant effect on methane production (See section 2.4.3)

6. *The data show that the bunker silo is the preferred storage system for AD farmers.*

It can be assumed that the storage system decision is directly related to the size of farm. This study found that a clamp/bunker is the most used by AD farmers, where most of them produce more than 10,000 tonnes/year (the maximum reported 50,000 tonnes/year). On the other hand bales is the most used by dairy farmers (they produce only 1,400 tonnes/year on average).

Clamps seem to be the best option when considering such large quantities of silage. Bags could also be a good option for farmers ensiling around 10,000 tonnes according to Wagner and Weber (2011). However, bales for AD farmers would be limited to the small scale farms since their storage capacity is around 650 kg (Braun et al., 2008).

It is remarkable, however, how small the number of farmers using bag silo is. The proportion expected was larger due to the advantages of the system shown in *Table 6*, for example, low initial cost, high flexibility and low DM losses are expected among others. A possible explanation for this could be a lack of knowledge, because this system is relatively new.

In addition it should to be mentioned that none of the farmers surveyed use tower silos, which corroborates the idea that the tower silo is no longer used in the UK. Despite the fact that studies from the USA have mentioned them, none of the recent UK studies do. This explains why the tower silo is not mentioned in the literature review.

7. *The data show that between farmers that use clamps, vertical walls are more common than the slanted ones.*

Besides bigger capacities, it is possible to achieve a better compaction with clamps than with other systems (Table 6). But to achieve the best compaction with a bunker silo, several authors (VitaPlus, 2012; Solórzano, 2010; Hartley, 2014) have noted the advantage of slanted walls against vertical ones. Slanted walls allow the tractor to roll the clamp more adequately, because it can get a lot closer so the side wall. However, a possible explanation for this result might be the farmers' ignorance about this benefit. Additionally, the vertical walls are considered to be cheaper because slanted walls will slightly reduce clamp capacity.

8. *The data show black polyethylene film is the preferred cover for AD farmers*

In section 2.4.5 it was reported that a number of recent studies proved that oxygen barrier film is a better inhibitor of the microorganisms responsible for aerobic deterioration during the silage making process than polyethylene films. Contrary to this, the results of the survey showed that most of the farmers are still using black polyethylene film. It is interesting to note that farmers who use oxygen barrier film use it in combination with black polyethylene film. It could be a good practice since extra weight and protection could be achieved by placing the black polyethylene over the oxygen barrier.

It was also found that none of the surveyed farmers are using white polyethylene despite less heat being accumulated than in black polyethylene films, and therefore, should be preferred (Muck, 2011; Norell et al., 2007). Therefore, white polyethylene films could partly solve the problem of clamp overheating that some farmers reported in the question about the main problems they face every year regarding silage quality.

9. *The data show that bad weather conditions, followed by poor silage management are considered to be the main causes of energy losses when making silage*

As noted in the literature review the extent and kinds of losses can be influenced by a number of factors (crop characteristics, weather conditions, storage system and management). According to (Kaiser et al., 2004) management is the most important factor influencing energy losses. From the farmer's point of view the most importance factor is bad weather conditions followed by bad silage management. They cannot have control of the weather, however, they can have full control of the ensiling process.

10. *The data shows that if they could start from starch, most of them would build narrower clamps*

This was one of the most important findings because it emphasises the problems that could be amended when making silage. Narrower clamps was the change most commonly indicated. There is a tendency to build clamps wider (Kautz, 2000). However, narrower and longer clamps would minimize the DM and energy losses when it is emptied.

An amendment of the water management (run off and leachate) systems was another change noted by farmers that is related to silo design. Leachate collection is a critical point in loss minimization because of its high energy content (Wagner et al., 2011). Therefore, it would be beneficial to collect all leachate possible, preferably separated from the rain water.

The purchase of modern and better machinery was the other point mentioned by farmers. This highlights again the importance of good compaction when making silage since machinery plays an important role in this. Adequate compaction, as mentioned before, will be also be influenced by the condition of crops at the point of ensiling and the storage system used.

These findings might not extend to all UK farmers who make silage for AD because of the small sample size. However, it could be concluded that the questionnaire was successful as it was able to give an idea of the practice of silage making in the UK. The discussion of the results, in combination with the other literature findings will be used to communicate to farmers the practices they should follow to achieve best quality silage for use in AD through a guide than can be found in Appendix C.

In addition, the issues where a certain lack of management knowledge appeared among the participants (use of covers, optimum chop lengths at ensiling and design considerations to minimize losses) should be priority topics for possible future educational programs.

5.2 Research limitations

Both limitations of previous research and limitations on the devised questionnaire influence directly in the reliability of the best practice guide.

5.2.1 Limitations of previous research

One of the biggest downfall in literature is the lack of agreement upon the effects of ensiling on methane formation. It is essential to know the effects of ensiling on methane production and the causes of that effect to be consistent recommending practices to achieve high energy yields.

Regarding the quality parameters, there is no study assessing the target values of silage for AD. Since the principles of preservation are the same, it is assumed that target values of silage for AD are the ones of well preserved silage for animal nutrition. This meets the objective of energy loss minimization mentioned previously. However, due to the relationship found between organic acids and methane yield noted in section 2.2, the method of assessing quality, and therefore energy losses, in silage for AD should be different.

In addition, due to the lack of research about the best practices for ensiling AD feedstock, some of the data (e.g. chop length) have been took from non-academic papers, and this may influence the reliability of the results.

5.2.2 Limitations of the questionnaire

One of the limitations of this research was the small sample size, because it was difficult to find significant relationships from the data. The low participation could be mainly attributed to three facts: (1) the period in which the questionnaire was open (July –August). According to Pennings et al. (2002) between May and October is the least preferred time period for farmers to answer questionnaires because of the harvesting time. (2) Internet access may be difficult for elderly farmers or farmers who reside in remote areas. (3) Posting invitations to participate in surveys may face rejection (Wright, 2005)

Another limitation of the research was the high dropout rate. It may be caused by (1) the length of the questionnaire, since dropout rate is directly and negatively correlated with questionnaire length (Harris, 1997), or (2) the kind of questions, since some of the data questions might not have been easy to answer.

Despite the fact that the target population was AD farmers, overall more answers were received from dairy farmers. The small number of AD farmers may reflect the fact that there is not a lot of AD farmers in the UK. This research would be stronger if more responses were received from AD farmers in the sample.

5.3 Recommendations for future research

As mentioned in the limitations, further study is required to understand the effects of ensiling on methane yields. These studies should also consider DM losses in order to know when the possible methane enhancement compensates the DM losses.

Since in most of the previous research, the additives assessed have little or no effect on methane production, further development of additives selective for ensiling of biogas feedstock would be required

Further research should also be carried out to investigate whether the quality demand on silage as the feedstock for biogas production is comparable to the quality standards of silage as animal feed.

As a result of the survey, two new topics that need further research have been identified: Chopping lengths recommended in *Table 5* require balancing of additional output and input of energy in order to know if the additional cost compensated the benefit of methane yield. Additives also require economical appraisal to know when their application is cost effective.

6 CONCLUSIONS

To date, there is no paper that summarises the current knowledge on silage making for AD. This research study aimed to collect and examine the information available in this regard. After analysing and discussing the obtained data from the literature and the questionnaire, the following conclusions could be drawn:

(1) Maize, grass, cereal and beet are the main feedstock for anaerobic digestion in the UK.

(2) The principles of ensiling to produce biogas or for animal feeding remain the same, however, acetic acid could be present in higher levels because it might be positive for biogas production since it enhances methane formation.

(3) Crops for AD use should be chopped to shorter lengths than the ones for cattle feeding.

(4) Crops for AD should be ensiled at a lower dry matter content than the ones for cattle feeding.

(5) Conventional additives, except heterolactic bacteria, reduce DM losses but have little effect on methane yield. There are still doubts (both among farmers and researchers) about when their application is cost effective.

(6) Clamps seem to be the best options to preserve AD feedstock because they can be designed to achieve larger capacities than the other systems. Silo bags could be a good alternative to clamps in smaller farms because of their high flexibility and low DM losses expected.

(7) Narrow clamps, slanted walls and effluent collection system help to minimize energy losses.

(8) Oxygen barrier is the best option for sealing because is the most air tight cover.

(9) Management is the most important factor influencing DM and energy losses, especially during filling and feed out.

Furthermore, through the questionnaire, the following has been identified as priority topics for possible future educational programs: use of covers, optimum chop lengths at ensiling and design consideration to minimize losses.

The findings of this research were used to develop a practice guide to communicate the practices that farmers should follow to achieve the best quality silage for AD. The guide includes recommendations for the whole ensiling process, from harvesting to feed-out.

As a result of the limitations found in the literature and some results obtained from the questionnaire, this study identified several avenues for potential future research; effects of ensiling on methane yields, development of additives selective for ensiling of biogas feedstock, quality demand on AD silage, and economic appraisal of shortenings chopping lengths and additives application. Further research in these topics could improve the guide that has been developed.

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APPENDICES

Appendix A. Online questionnaire

This appendix shows the questionnaire that was posted on different internet media (Twitter, UK farming forums, renewable energy webpages).

1. What is your silage used for?
    a. Biogas production
    b. Livestock feeding
    c. Other. *Please, specify*
2. (If biogas production) Is any other feedstock used for the biogas production?
    a. No, the energy crop is the only feedstock
    b. Yes, animal waste (e.g Muck and slurry)
    c. Yes, food waste
    d. Other. *Please specify*
3. Which of the following crops do you grow for silage?
    a. Maize
    b. Sugar beet
    c. Grass
    d. Whole crop
    e. Other. *Please, specify*
4. What system do you use to preserve your silage?
    a. Clamp/bunker silo
    b. Field clamps or pile
    c. Bagged silage (Ag-bags)
    d. Big bale
    e. Other. *Please, specify*
5. Who designed and manufactured your silage storage system?
6. How many tonnes of silage do you make a year? (tonnes)
7. How old is your silage storage system? (years)
8. How many of them do you have?

9. What is the total storage capacity of your largest silage clamp? (tonnes)

Silage clamp only

10. What is the length of the sidewalls of the clamp from front to back?(m)
11. What is the design of the sidewalls?
    i. Slanted side walls
    ii. Vertical side walls
    iii. I do not know
12. (if slanted) What is the angle degree in the side wall (approximately)?
    i. <10º
    ii. 10-15º
    iii. 15-20º
    iv. 20-25º
    v. >25º
    vi. I do not know

Silage or field clamp only

13. What is the maximum height you fill your silage clamps to? (m)
14. What kind of covers do you use to seal the clamp?
    i. Black polyethylene film
    ii. White polyethylene film
    iii. Oxygen barrier
    iv. Other. *Please, specify*
15. How many layers are used?
16. Who do you purchase them from?

17. When you are emptying your silage clamp what is the area of the exposed silage face (approx.)?(m^2)
18. What is the approximate crop dry matter content at point of ensiling? (%)
19. What is the crop chop length? (mm)
20. Do you use any of the following additives when making silage?
    a. Chemical preservatives (E.g. formic acid)

b. Inoculants of lactic acid bacteria (LAB)
c. Molasses addition
d. No
e. Other. Please specify

21. What do you monitor when making silage?
   a. Compaction
   b. Silage pH
   c. Lactic acid concentration
   d. Acetic acid concentration
   e. Butyric acid concentration
   f. None of them
   g. Other. *Please, specify*

   If you measure compaction

   What is the average compacted density?(kg/m3)

   If silage pH

   What is the PH of the silage when you remove it from you silage clamp?

   If lactic acid concentration

   What is the silage lactic acid concentration when you remove it from your silage clamp?(%DM basis)

   If acetic acid concentration

   What is the silage acetic acid concentration when you remove it from your silage clamp? (%DM basis)

   If butyric acid concentration

   What is the silage butyric acid concentration at the when you remove it from your silage clamp?(%DM basis)

22. What is the most important silage quality parameter for you? <u>Please, select TWO</u>
   a. Dry Matter
   b. Colour

c. Odour

d. Rigidity

e. Density

f. pH

g. Mould

h. Yeast

i. Other. *Please specify*

23. In your storage system, in your opinion, where does dry matter loss come from (mainly)? Use the scale below to select the suitable number, being 1 strongly disagree and 5 strongly agree

a. Poor harvesting

b. Wrong size storage system

c. Wrong design of storage system

d. Poor quality of covers

e. Mistakes during ensiling process (poor silage management)

f. Bad weather conditions during ensiling

g. Other. Please specify

1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5

24. What is the biggest issue with your silage which you face every year? Please specify

25. How important are the following things for you? Use the scale below to select the suitable number, being 1 strongly disagree and 5 strongly agree

a. Safe working environment on clamp

b. Ease of use regarding covers

c. Labour time saving due to technology

d. Quick return on investment when building a new clamp

e. Increase of yields by avoiding losses

f. After sales support

1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5

26. And if you could start from scratch, what would you do differently?

27. Are you planning to invest in a new storage system?

a. Yes
b. No

28. Which design would you go for?
    a. Field clamp
    b. Vertical wall clamp
    c. Sloped wall clamp
    d. Ag-bag
    e. Other. Please, specify

29. If there would be a possibility to get trained in modern silage management, would you invest in a training?
    a. Yes
    b. No

Appendix B. Questionnaire data analysis

This section shows the data collected through the questionnaire. Tables presented are the result of the data analysis. Numerical data were analysed using the mean, standard deviation, coefficient of variation (CV), maximum and minimum. On the other hand, qualitative data from close-ended questions were analysed by identifying the percentage of responses per category and dependence between some qualitative categories were compared by using the Pearson χ^2.

Question 1: Use of the silage

n: 40 Rows: use of the silage Columns: statistic parameters

	n	%
Biogas production (AD farmers)	12	30
Animal feeding (Dairy farmers)	28	70
Total	40	100

Question 2: Use of another feedstock

n: 12 Rows: feedstock Columns: statistic parameters

	n	%
No	7	58
Yes, animal waste	4	33
Yes, food waste	1	8
Total	12	100

Question 3 and 4: Crops and storage system used

n: 40 Rows: crop used Columns: group of farmers

Crop	Total	Group of farmers: Dairy farmers	Group of farmers: AD farmers	Pearson χ2 Group of farmers: Dairy farmers	Pearson χ2 Group of farmers: AD farmers	p-value
Maize						0.001
Yes	22	4	8	8.61	3.69	
%	28.2	14.3	63.6			
No	17	24	4	20.10	7.89	
%	71.8	85.7	36.4			
Grass						0.02
Yes	38	28	10	26.6	11.69	
%	94.9	100	81.8			
No	2	0	2	1.40	0.62	
%	5.1	0	18.2			
Cereal						0.001
Yes	10	4	6	6.46	2.54	
%	23.1	14.3	45.5			
No	30	24	6	28.97	11.38	
%	76.9	85.7	54.5			
Beet						0.01
Yes	3	1	2	2.15	0.85	
%	7.7	3.6	18.2			
No	37	27	10	25.85	10.15	
%	92.3	96.4	81.8			

n: 40 Rows: Storage system Columns: Group of farmers

Crop	Total	Group (use of the silage): Animal feeding	Group (use of the silage): Biogas production	Pearson χ2 Group (use of the silage): Animal feeding	Pearson χ2 Group (use of the silage): Biogas production	p-value
Clamp/bunker						0.001
Yes	28	17	11	19.60	8.40	
%	70.5	60.7	91.7			
No	12	11	1	19.60	7.70	
%	29.5	39.3	8.3			
Field clamp/pile						0.01
Yes	5	2	3	3.50	1.50	
%	12.5	7.1	25.0			
No	35	26	10	24.50	10.50	
%	87.5	92.9	75.0			
Bag silo						0.007
Yes	2	0	2	0.47	2.48	
%	5.0	0.0	16.7			
No	38	28	10	21.00	8.25	
%	95.0	100.0	83.3			

Bales						<0.001
Yes	22	21	1	2.10	0.83	
%	55.0	75.0	8.3			
No	18	7	11	25.20	9.90	
%	45.0	25.0	91.7			

n=40 Rows: Storage system Columns: Crop

	Maize	Grass	Whole crop cereal	Beet	Total
Silage clamp or bunker	12	22	11	3	48
Field clamp or flat pad	1	4	2	0	7
Bagged silage (E.g Ag-bag)	2	1	0	0	3
Baled and wrapped	0	20	1	0	21
Total	13	46	13	3	

Question 5: Clamp manufacturing and installation

n=17 Rows: Manufacturer Columns: Group of farmers

	Total	Dairy farmers	AD farmers
Themselves	9	7	2
Assistance from a company	8	4	4

Mentioned companies: ACP, Form construction, Bock Whites concrete, Brooks and Wood

***Questions 6, 9, 10, 13, 17*: Farm size and clamp dimensions**

n=17 Rows: Size parameters Columns: Statistic parameters

	Average	Standard deviation	CV (%)	Min	Max

Total tonnes/year					
AD farmers	2,333.00	16,049.00	71.90	1,000.00	50,000.00
Dairy farmers	1.42	1,545.83	108.67	100.00	6,000.00
Total	7,125.50	12,598.02	176.80	100.00	50,000.00
Capacity of the largest clamp (tonnes)					
AD farmers	15,700.00	128,833.00	82.06	500.00	40,000.00
Dairy farmers	865.00	386.00	44.60	400.00	1,500.00
Total	7,009.40	11,191.90	159.70	400.00	40,000.00
Height (m)					
AD farmers	5.00	2.00	37.01	4.00	9.00
Dairy farmers	5.50	1.60	28.40	3.50	8.00
Total	5.60	1.70	31.00	3.50	9.00
Length (m)					
AD farmers	59.00	34.00	57.41	25.00	130.00
Dairy farmers	20.28	15.10	74.30	3.00	50.00
Total	36.70	31.30	85.10	3.00	130.00
Expose face (m2)					
AD farmers	121.50	81.48	0.67	17.00	255.00
Dairy farmers	42.15	24.45	0.58	10.00	80.00
Total	71.91	65.87	0.92	10.00	255.00

Question 11, 12: Sidewalls

n=17 Rows: Wall design Columns: Group of farmers

	Total	Dairy farmers	AD farmers
Slanted walls	7	5	2
%	41	50	29
Vertical walls	10	5	5
%	59	50	71

Question 14, 15, 16: Covers

n=21 Rows: Type of cover Columns: Group of farmers

	Total	Dairy farmers	AD farmers
Black polyethylene film	15	10	5
White polyethylene film	1	1	0
Oxygen barrier	5	4	2

n=21 Rows: Number of layers Columns: Statistic parameters

	Average	Standard deviation	CV (%)	Min	Max
Dairy farmers	1	0.80	64.00	1	3
AD farmers	2	0.43	21.32	1	3
Total	2	0.60	31.97	1	3

Mentioned sellers: Mortons, Bock UK, Glanbia food, Visqeen, Coop, Maizetech, Wynnstay and local stores

Question 18: Dry matter

n=21 Rows: Crop Columns: Statistic parameters

	Average	Standard deviation	CV (%)	Min	Max
Maize (n=5)					
AD farmers	31.00	2.10	6.90	28.00	33.00
Dairy farmers	35.00	0.00	0.00	35.00	36.00
Total	31.80	2.48	7.80	28.00	35.00
Grass (n=20)					
AD farmers	27.70	7.60	27.40	20.00	40.00
Dairy farmers	30.70	6.83	22.29	20.00	50.00
Total	30.17	7.05	23.39	20.00	50.00
Cereal (n=5)					
AD farmers	31.70	8.50	26.80	20.00	40.00
Dairy farmers	30.00	10.00	33.30	20.00	40.00
Total	31.00	9.17	29.60	20.00	40.00
Beet (n=1)					
AD farmers	15.00	0.00	0.00	15.00	15.00
Dairy farmers	0.00	0.00	0.00	0.00	0.00
Total	5.00	0.00	0.00	5.00	5.00

Question 19: Chop length

n=21 Rows: Crop Columns: Statistic parameters

	Average	Standard deviation	CV (%)	Min	Max
Maize (n=5)					
AD farmers	8.30	1.20	15.00	7.00	10.00
Dairy farmers	7.00	0.00	0.00	7.00	7.00
Total	8.00	1.22	15.30	7.00	10.00

Grass (n=20)					
AD farmers	18.40	16.10	87.30	7.00	50.00
Dairy farmers	57.30	63.80	111.00	10.00	250.00
Total	47.60	58.30	123.00	7.00	250.00
Cereal (n=5)					
AD farmers	21.70	20.00	92.50	7.00	50.00
Dairy farmers	22.50	2.50	11.10	20.00	25.00
Total	22.00	15.60	70.90	7.00	50.00
Beet (n=1)					
AD farmers	5.00	0.00	0.00	5.00	5.00
Dairy farmers	0.00	0.00	0.00	0.00	0.00
Total	5.00	0.00	0.00	5.00	5.00

Question 20: Additives

n=24 Rows: Additive Columns: Group of farmers

		Total	Dairy farmers	AD farmers
Chemical preservatives				
	n	0	0	0
	%	0	0	0
LAB				
	n	6	6	0
	%	25	31	0
Molasses				
	n	0	0	0
	%	0	0	0

Question21: parameters monitored

n=23 Rows: Parameter Columns: Group of farmers

		Total	Dairy farmers	AD farmers
Compaction				
	n	14	10	4
	%	60.87	55.56	80
DM				
	n	19	15	4
	%	82.61	83.33	80
pH				
	n	8	6	2
	%	34.78	33.33	40

Lactic acid				
	n	3	3	0
	%	13.04	16.67	0
Acetic acid				
	n	1	1	0
	%	4.35	5.56	0
Butiric acid				
	n	1	1	0
	%	4.35	5.56	0

Question 22: two main important parameters

n=22 Rows: Parameter Columns: Group of farmers

	AD farmers	Dairy farmers
DM	66.7	62.5
Colour	16.7	18.8
Odour	0.0	18.8
Rigidity	0.0	0.0
Density	0.0	0.0
pH	16.7	18.8
Yeast	0.0	0.0
Protein content	0.0	25.0
Milk yield	0.0	12.5
Digestibility	0.0	62.5
Methane potential	100.0	0.0

Question 23: main causes of energy losses

n=16 Rows: Causes Columns: Opinion

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
Poor harvesting	3	4	2	6	1
Wrong design of storage system	6	3	6	3	1
Wrong size of storage system	4	4	6	3	0
Mistakes during ensiling process (poor silage management)	1	2	6	7	3
Poor handling of inoculants	2	4	12	1	0
Bad weather conditions during ensiling	0	1	6	7	5
Poor quality covers	2	2	8	6	1

Poor effluent management	3	4	8	2	1

Question 25: points of importance when making silage

n=16 Rows: points of importance Columns: Opinion

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
Safe working environment	1	2	1	4	8
Ease of use regarding covers	0	2	0	10	4
Labour time saving	0	0	4	9	3
saving Quick return on investment	2	2	4	7	3
Increase of yields by avoiding losses	0	0	1	9	6
After sales support	2	6	4	2	2

Question 27, 28, 29: Investment

n=17 Rows: Investment Columns: Group of farmers

	Total	Dairy farmers	AD farmers
		In a new storage system	
Yes	4	3	1
%	23.53	25.00	20.00
No	13	9	4
%	76.47	75.00	80.00
In a training in modern silage management			
Yes	5	2	3
%	29.41	16.67	60.00
No	13	9	4
%	70.59	83.33	40.00

Appendix C. Best practice guide

This appendix shows the guide that has been developed (as result of the literature findings and the questionnaire discussion) to communicate the practices that farmers should follow to achieve the best quality silage for AD.

Best practice guide for silage system in Anaerobic Digestion

Biogas plants have to be fed continuously while crops accumulate seasonally. Therefore, most of the time, crops needs to be preserved, and ensiling is the preferred procedure to do it.

When making silage for AD, the preservation of DM and energy during storage is the main concern. Studies demonstrate a remarkable reduction of biogas yields when good practices are not followed.

This guide is based on research and aims to help farmers maximise energy outputs from silage.

BIOGAS CROPS

A broad variety of crops can be used as biogas feedstock. The main ones used in the UK are:

Maize

- Maize can be successfully grown in most areas of the UK. Crop yields are dependent on local conditions.
- Maize has the potential to produce high methane yields and it is easy to store.

Grass

- Grass is suitable for growth across the UK because of the wet climate. It is a very versatile crop.
- Lower methane yields per ha

Whole-crop cereal

- Almost all types of cereals are suitable for producing whole-crop cereal silage. However, rye and triticale are the cereals that produce higher DM in most locations.
- High whole-crop yields, but lower methane yields than other crops

Beet

- Beet is suitable for cropping across most of the UK and a high yield is achieved.
- High methane output: Beet has a shorter retention time in the digester than the other crops because of the high sugar content.
- Two major difficulties exist when beet is used as biogas feedstock:
  - Soil remaining on the beet has to be removed
  - Storage is more difficult than for other crops because of its low DM content

QUALITY SILAGE FOR AD

Once the crop has been grown and harvested its energy content needs to be preserved until it is fed into the digester.

The principles of ensiling to produce biogas or for animal feeding remain the same; low pH, high lactic acid, prevention of enterobacter and clostridia growth, prevention of silage losses and aerobic stability after opening the silo. However, contrary to animal feeding, acetic acid could be present in higher levels because it might be positive for biogas production since it enhances methane formation[1]. This means that DM preservation is in the only critical factor in the production of biogas, because DM losses due to the formation of some organic acids may be compensated by improving crop digestibility[2].

The key factors in achieving high quality silage for AD are the storage of the crop at optimum moisture content and particle size, an adequate storage system and proper management (from filling to feed out).

Moisture content

The concentration of lignocellulose, which is not easy to degrade by anaerobic processes, increases with time. Therefore, crops for biogas production are usually harvested at a less mature stage of growth in comparison with animal feeding. This means that there is a focus on harvesting at a lower dry matter content to encourage fermentation. Table 1 show the optimal DM values for each of the crops.

Table 1. Recommended harvest time and optimal dry matter content of selected energy crops

Crop	Harvest time	Optimal DM (%)
Maize	Mid September-mid October[3] (Milk to wax ripeness)	27-31[4]
Grass	First cut end of May[3] (First cut before ear emergence)	26-30[5]
Whole-crop cereal	Mid June[4] (Grain at milky ripe stage)	30-36[4]
Beet	Mid November[6]	20-23[6]

Lower dry matter levels will increase leachate production, which is associated with significant energy losses.

Higher dry matter levels will reduce methane yields through the production of silage which is more difficult to degrade. Moreover, this silage cannot be optimally compacted [6].

Chop length

For cattle feeding, the particle size needs to be long enough to float in the rumen and maintain the rumen fibre. However, for silage for biogas production, crops should be chopped to shorter lengths[7]. Shorter lengths are beneficial because they:

- Minimize dry matter losses, due to enhanced compaction and oxygen elimination in the silage.
- Enhance silage degradability in the digester, as a result of an increased surface area for the bacteria to break down the crop[8].

The optimal values for each of the crops are in the Table 2.

Table 2.Optimal chop length for selected crops

Crop	Optimal chop length (mm)
Maize	7-10[4,11]
Grass	4-10[5]
Whole cereal	7-12[10]
Beet	-*

*The best method is to ensile the whole beet (whole beets produce less effluent than chopped beets) and chop it before going into the digester[7,8]

[1] Ploechl et al., 2009 [2] Idler et al., 2007 [3] Kalač, 2011 [4]KWS UK Ltd, 2014 [5]Prochnow et al., 2009 [6] Gülzow, 2012 [7] Barnhill et al., 2009 [8]*Carley,* 2013 [9]Wagner et al., 2011 [10] Elsoms, 2014b [11]Herrmann et al., 2011

Additives

Different additives are available to help produce high quality silage.

✓ The use of additives is recommended when there is risk of aerobic deterioration.

✗ In other cases (e.g. improved fermentation velocity or fermentation pattern), the additional energy production may not compensate the cost of the additive.[1]

It has been established that heterofermentative inoculants improves the energy conservation of the harvested material (improves aerobic stability) and have a positive effect on methane formation[1, 2, 3]

Storage system

Four different storage systems are currently being used in the UK: clamp (or bunker), field clamp (or pile), bag silo (Ag-bag) and bales. There are clear differences between systems, in terms of costs, DM losses, flexibility, durability, work involved, crop suitability, capacity, compaction and foot print. The question of which method is best for conserving silage can be considered from many different perspectives. Therefore, it is important for each farmer to evaluate their own unique situation.

Crop suitability

Good quality silage can be obtained by using any of the storage systems, as long as the design and management of the silo is appropriate. However, in the case of beet, ensiling in bales or piles creates the risk of poor fermentation and DM losses increase because of its moisture content.[4] (see Table 3)

Table 3. Silo suitability depending on the farm size

Feedstock	Clamp/ bunker	Pile/field clamp	Bagged (Ag-bags)	Big bale
Maize	✓	✓	✓	✓
Grass	✓	✓	✓	✓
Whole crop cereal	✓	✓	✓	✓
Beet	✓	✗	✓	✗

Capacity

The high quantity of silage fed into the digester) means storage systems for AD silage tend to be relatively large. In a medium size installation up to 10,000 tons of silage are prepared per year[5] Clamps can be designed to achieve larger capacities than the other systems[4], which makes it the preferred system for feedstock preservation. An alternative to clamps in medium size farms is the bag silo. In smaller farms bales can also be applied for storage (See Table 4).

Table 4. Silo suitability depending on the farm size

Farm size	Clamp/ bunker	Pile/field clamp	Bagged (Ag-bags)	Big bale
Large scale (>10,000 tonnes/year)	✓	✓	✗	✗
Medium scale (5,000-10,000 tonnes/year)	✓	✓	✓	✗
Small scale (<5,0000 tonnes/year)	✓	✓	✓	✓

[1]Bannemann, 2009 [2]Ploezt et el, 2009 [3]Nusbaunn,2012 [4] Kaiser et al., 2004 [5]Braun et al., 2008

Table 5. Other factors influencing silo election				
Factor	**Clamp /bunker**	**Pile/field clamp**	**Bagged (Ag-bags)**	**Big bale**
Construction cost	High	Low	Low	Low
Cost/tonne of storage DM	Low	Low	High	High
Flexibility	Inflexible storage	Capacity	Sitting and capacity	Sitting and capacity
Machinery required	Conventional equipment	Conventional equipment	Specialized equipment	Conventional equipment
Compaction	Good	Lower density than bunkers	Adequate, but lower than bunkers	Adequate
DM losses expected	Medium	Highest	Lowest	Medium
Labour requirements for filling	More than for bags and bales	More than for bags and bales	Modest	The least
Footprint	The smallest	Larger than in bunkers	Larger than bunker and pile	The largest

Other factors

Despite piles possibly meeting capacity requirements of a large farm, its use is not recommended because the required compaction often cannot be achieved without side walls[1]. In addition, piles have a higher risk of high energy and DM losses if recommended practices are not followed[2]. On the other hand, silo bags result in low dry matter losses than other systems due to the rapid exclusion of air[2].

Design considerations

Especially for clamps, design plays an important role in loss minimization

- **Size:** By reducing the exposed face, clamp losses are minimized, hence, clamps should be sized to match the recommended feeding rates shown in Table 7[3].
- **Side walls**: slanted walls are recommended because they allow the tractor to roll the clamp more effectively, since it can get a lot closer so the side wall. Consequently, slanted walls allow for better compaction to be achieved than vertical walls[4].
- **Water collection system**: In order to minimize energy losses, it is important to c contain the silage effluent (separately from rain water if possible) to feed it directly into the digester[5].

Filling and compaction

The silo structure should be filled quickly, but prior to this it will be essential to clean the ground or floor before ensiling to prevent contamination, especially with beet silage[6].
Irrespective of the type of storage system, the plant material must be compacted as densely and as quickly as possible. Filling the silo at the recommended dry matter content and chop length (Table 2, 3) improves compaction and does not allow the ingress of air. The expected densities when ensiling at optimal conditions are shown in Table 6.

Table 6. Compaction expected at optimal dry matter content		
Crop	**DM %**	**Density (kg/m^3)**
Maize	27-31	230[7]
Grass	26-30	210[8]
Whole-crop cereal	30-36	230[6]
Beet	20-23	*

*No data found

[1]Kaiser et al., 2004 [2]Norell et al., 2007 [3]Saxe, 2007 [4] Solórzano, 2010 [5]Wagner et al., 2011 [6]KWS UK Ltd., 2014 [7]Schaumann Bioenergy, 2013 [8]DLG, 2012

For clamps:

- In large clamps where filling takes several days, the material should be compacted with the progressive wedge technique[1].
- Compress silage with a tractor

For bag silo:

- Use good filling machine

For bales:

- Bale tightly

Figure 1. Progressive wedge technique[2]

Sealing

Well-sealed storage prevents the air and water from entering and therefore will help to ensure minimum aerobic losses.

For clamps:

- Seal immediately after filling
- There is evidence that the oxygen barrier cover is the most air tight cover.
- Extra weight and protection could be achieved by placing the black polyethylene film over the oxygen barrier.
- Seal ends and sides carefully

For bag silo:

- Seal while it is filled
- Seal ends carefully

For bales:

- Wrap immediately after baling
- Seal ends carefully

It important to inspect plastic covers and bags in order to repair possible holes that can cause additional spoilage.

Feed-out

As soon as the silo is opened for feeding, the silage will start to deteriorate[1]. It is recommended to remove at least the amount of silage per day shown in Table 7 to minimize the deterioration in the face exposed to oxygen.

Regardless of the removal practice used, a smooth and tight face should be maintained.

Table 7. Recommended removal rates[3]

Storage type	Cold weather (cm/day)	Warm weather (cm/day)
Clamp/bunker	10	16
Field clamp/pile	10	16
Bag silo	10	16

Managing effluent

Leachate collection is a critical point in loss minimization because of its high energy content. Therefore, it should be retained and fed into the digester.

[1] Moran, 2005 [2]Huhnke, [3]*Muck, 2000*