AUSTRALIAN MEAT PROCESSOR CORPORATION

FINAL REPORT – Organic waste management at abattoirs

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Project 2: Development of methodologies for characterising paunch waste (PW) to inform dewatering/drying technologies

1.0 Executive Summary

Paunch waste has potential to become a site specific waste to energy stream for the red meat processing industry. Numerous possible end uses have been identified for paunch waste such as pyrolysis, incineration, or co-combustion (e.g. Ricci 1977, eds Witherow & Scaief 1976). However, the high initial moisture content of paunch has inhibited the implementation of resuse in the red meat processing industry. Very little research has been done to understand the characteristics of paunch to enable informed decisions on suitable treatment methods.

A review on the current understanding of paunch characteristics relating to drying identified a lack of knowledge on the inherent properties of paunch such as drying rates and equilibrium moisture content. This lack of knowledge has held back the implementation of paunch reuse strategies.

To inform this lack of knowledge a detailed methodology has been developed to inform paunch drying characteristics. Drying rates based on temperatures of 35, 45, and 55°C and relative humidities of 40, 60, and 80% were determined along with matching equilibrium moisture contents. The drying rates were primarily affected by paunch type, paunch variability, and relative humidity with temperature having a lesser effect than expected. Equilibrium moisture content ranged from approximately 7 to 13 % for relative humidities ranging from 40 to 80% in the temperature range of 35 to 55°C. Dryer designs should therefore accommodate relative humidity as a high temperature dryer will not perform well if the humidity is not controlled.

Calorific values for grass and grain type paunches were calculated and determined to be between 17.3 – 20.2 MJ/kg. This showed paunch has the potential to replace nearly half of the annual coal usage for a medium sized abattoir.

Further work should continue into paunch characteristics and into the possibility of using paunch as a rewetting agent for coal. Solar dryer designs should be investigated with a focus on humidity control inside the dryer.

2.0 Introduction

Paunch is the partially digested feed from the first stomach of ruminant animals such as, sheep, pigs, and cows and may be a viable fuel source for use in co-combustion units, as a coal substitute, or pyrolysis (e.g eds Witherow & Scaief 1976, Bridle 2011). Early energy measurements done with a Parr Oxygen Bomb Calorimeter showed that paunch has an average energy content of 16.7 MJ/kg (Ricci 1977). This energy content is comparable to other biomass crops such as switch grass which has an energy content of 18.4 MJ/kg (McLaughlin et al. 1999).

The main problem regarding paunch for use as a biomass is its moisture content. The high moisture content (around 80 -85% when dewatered of surface water (Ricci 1977, eds Witherow & Scaief 1976)) of undried paunch makes it a non-viable biomass, instead the paunch needs to be dried to below 70% moisture content to become useful. Bridle (2011) stated that paunch with a 70% (wet basis) moisture content, while burnable, has little or no recoverable energy and therefore burning paunch at this moisture content would only be beneficial as a waste disposal method.

Drying rates, equilibrium moisture contents and calorific values need to be known before a suitable method can be determined for drying paunch. A fundamental understanding of these characteristics will allow for the design and modelling of the most suitable dewatering/drying technology.

In previous work there has been a tendency to select a particular drying system and then investigate whether it can dry paunch rather than understand paunch characteristics and then design an optimum drying system. With such variation in design it is important to select the correct dryer for a specific product. Drying times, economic viability, and product handling are all reliant on appropriate dryer selection which is in turn reliant on the specific properties of the product.

During the 1970s and early 80s a number of studies were published regarding the handling/treatment methods and possible benefits of paunch, although research on this topic had decreased until recently (figure 1). As there are a limited number of papers relating to paunch drying the below literature review contains comprehensive highlights of the main findings associated with each paper.

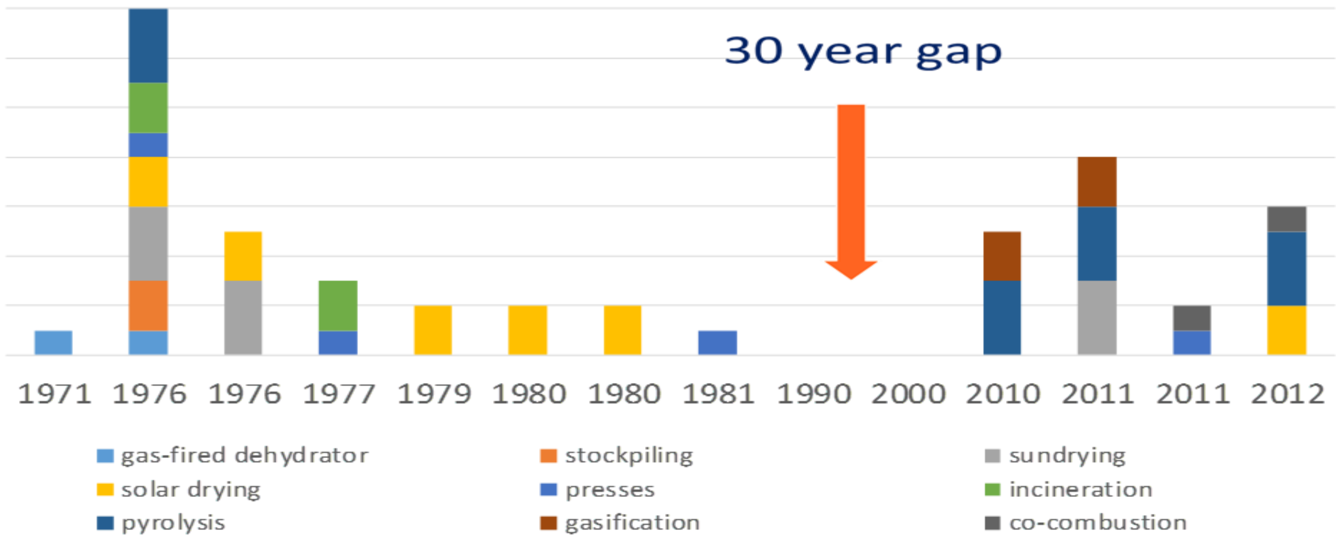

Figure 1- Research performed into paunch as a biomass. The stacked columns are representative of the information contained in each paper (not representative of multiple papers).

2.1 Literature Review

As early as 1971, Baumann (1971) made recommendations to the beef processing industry that all abattoirs should install dehydrators for both blood and paunch for beneficial end uses such as a feed additive and reducing wastewater pollution. In an attempt to reduce environmental damage and financial burdens at abattoirs eds Witherow and Scaief (1976) identified numerous methods for handling paunch. Of particular interest are: lagooning or stockpiling, rotary dryers, presses, solar & air drying (Yin and Farmer as cited in eds Witherow & Scaief 1976), incineration, and pyrolysis.

Yin and Farmer (as cited in eds Witherow & Scaief 1976) claimed to have successfully used sun/air drying to dry paunch to 16 to 20 % moisture content in a week. They turned a 10 cm layer of paunch daily to stop a crust forming along the top. However, sun drying or open air drying (exposing a product to the sun) is not a feasible treatment method due to the many inherent disadvantages. Sun drying can be time consuming with a lengthy sun exposure time, it is dependent on climatic conditions and the product is exposed to the elements such as rain, possible infestation from insects, possible odour problems, and requires a large surface area for spreading the product (Belessiotis & Delyannis 2010). These disadvantages can be seen in some of the problems encountered by Yin and Farmer in their study such as rain rewetting the paunch, fly, and odour problems. These problems were dealt with through the building of a solar still with mechanical agitation as opposed to hand stirring of the paunch (eds Witherow & Scaief 1976).

Ricci (1977) set about to design and demonstrate a fluidized bed incineration system to handle the paunch waste stream produced by (beef) abattoirs. At the time of printing Ricci (1977) implied that this design would proceed and results in the implementation be presented in a subsequent report. Data are not readily available to indicate whether this study was successful or to allow investigation into whether it would be economically viable in today's market.

A study by Farmer, Brusewitz and Moustafa (1979) identified that solar dried paunch has the potential to become a fuel source for abattoirs. They modified a simple solar still design to test their hypotheses on drying paunch. The results from the Farmer, Brusewitz and Moustafa (1979) study such as:

'An open mesh tray bottom significantly increases the drying rate. Breaking of the crust on the second or third day increases the condensate production rate. Continued stirring on subsequent days is not necessary (Farmer, Brusewitz & Moustafa 1979, p 224)'. Should be applicable to all types of solar dryers, and not just modified solar still designs.

Of particular interest is Griffith and Brusewitz (1980) study using a tunnel dryer to determine a paunch drying constant as a function of air relative humidity, material depth, and time after slaughter in order to optimize paunch moisture reduction. To obtain a drying constant Griffith and Brusewitz (1980) used a set temperature of 35°C with varying relative humidity at 20%, 50%, and 80%. Their study found that paunch composition (i.e. grass or grain fed) had the greatest effect on drying rates compared to humidity, age, or depth. These authors found that the drying time for a high concentrate ration feed was five times higher than that for a high forage diet. There was also an age - humidity relationship for medium to high humidity and fastest drying occurred at low humidity and shallow depth. Griffith and Brusewitz's (1980) data suggests that there is no effect on the drying rate for depths of 2cm to 10cm. However, they only used solid wall drying pans which therefore restricted the flow of moisture transfer to the upward direction. Older paunch can also reduce the drying constant along with high humidity. It was found that all drying constants were high for humidities up to 20%. While the work demonstrates some interesting relationships for drying paunch there does appear to be some (possibly typographical) errors in their reported numerical drying constants.

Farmer, Farouk, and Brusewitz (1980) using direct solar energy and solar-regenerated desiccant for low-insolation days found that they could reduce paunch moisture from 80% to 30% in 5 days. The dryer was designed to operate independently as a modified solar still on high insolation days or in conjunction with the desiccant during low insolation days. This study was noteworthy due to the size of the dryer (pilot-plant size as opposed to laboratory studies) and an innovative concentrating solar air collector.

Brusewitz, Moustafa and Farmer (1981) claim that pneumatic dewatering of paunch to remove loosely held moisture could be done with less energy and in a fraction of the time compared to evaporation techniques. Their study showed that dewatering soon after slaughter removed the most amount of liquid and that storage at low temperatures (10°C) resulted in 10 to 50% less water being removed. Most abattoirs currently use some form of dewatering of paunch, as seen in the current best practices, to separate the liquid and solid waste stream.

Bridle (2010) undertook a desktop study to review waste pyrolysis using paunch and DAF sludge (DAF sludge is fat and protein, meat slivers and fat, which gets into the wash water). The study identified that there are potential economic and environmental benefits using abattoir waste for pyrolysis or gasification. However, the report showed that the paunch and DAF sludge would need to be dried to 20% moisture content (80% total solids) or below prior to being used. As moisture contents higher than 20% would require too much energy from the pyrolyser thus producing a poor quality syngas, rendering it uneconomical.

After the previous desktop study Bridle (2011) undertook to design a program to sun dry, characterise, and use paunch and DAF sludge in two systems; Pacific Pyrolysis, and BiGchar gasification. The study predicts that pyrolysis and gasification are the most attractive for the meat industry with possible gains of GHG credits up to 1 tonne CO2-e and net energy credits up to 3.2 GJ per tonne of feedstock. However, he claims that thermally dried paunch and DAF sludge is not economically viable for co-combustion in boilers, whereas dewatered paunch is viable for co-combustion due to some environmental benefits and as a disposal method. The economic factor that made co-combustion unattractive was the high cost associated with drying the paunch. However, this was based on the cost and maintenance of a fossil-fuel run dryer not a solar dryer.

The dewatered paunch approach as a waste disposal system was economically attractive due to paunch only needing a total solid of 30% to burn self-sustainingly. This is around the total solid count from dewatering systems such as a screw press. However, this method was only suggested for use as a waste disposal method with little or no energy recovered. The process to dry the paunch for the two system tests and for use in the desktop study was done by spreading 2 to 3 m^2 of paunch over an area of 25 m^2 at a depth of 10 to 15 cm and sun dried over a period of two weeks. The area was increased to 50 m^2 after the first week and the paunch was hand stirred twice a day. As with Yin and Farmer (as cited in (Witherow & Scaief 1976)) sun drying is not a viable drying method. Interestingly though Yin and Farmer (as cited in Witherow & Scaief 1976) stirred their paunch once a day and dried paunch in half the time as Bridle (2011) at a similar depth. This could possibly be explained by the disadvantages of sun drying such as climatic conditions affecting the drying rate.

Bridle (2011) then undertook an assessment of dewatered paunch for use in a co-combustion boiler. The results of this study show great promise for paunch waste to be used in co-combustion with a net economic benefit of $1.58 million over 20 years for use in existing boilers and a net economic benefit of $2.85 million over 20 years for a new boiler able to co-fire biomass. Paunch could provide 30% of boiler fuel requirements with potential for GHG credits. There were minor environmental impacts and no impact on boiler combustion performance (at 5% paunch rate with total solids of 30%). The environmental impact of increased stack emissions remained within regulatory guidelines.

These studies show that paunch has the potential to become a beneficial waste product if the initial moisture content can be reduced. Recoverable energy from paunch (although variable) is possible. As there has been very little research into paunch it would be beneficial to characterise paunch as Griffith and Brusewitz (1980) set out to do with their drying rates and to apply this knowledge to selecting a drying method. Industries such as the grain industry understand their products characteristics and select drying equipment appropriately and successfully. It seems appropriate that if paunch is to be utilized as a beneficial waste to energy stream that a similar understanding of its characteristics are needed before a suitable method for paunch handling can be designed.

2.2 The project objectives and approach

The aim of this project is to develop a methodology to determine the drying properties and characteristics of paunch. Characterisation of the material will enable optimum paunch drying times and conditions to be achieved which will assist in determining whether dried paunch is a viable biofuel.

2.3 Any limitations to the research.

This project has limited itself to three temperature ranges (based on time) with three relative humidities for thin layer drying rates and equilibrium moisture contents. This will limit optimum drying condition recommendations. Further limitations were found to be a problem with the operation of the 500g load cell at the higher temperature/humidity range (55°C 60 – 80% RH) and with the environment chamber at 55°C 80% RH operating range.

Other information outside the scope of this project includes the suitability of the dryer such as: economic feasibility, ability of the dryer to cope with the daily on-site production of fresh paunch, and the suitability of the end product for uses such as co-combustion.

3.0 Project Objectives - Paunch management and handling

Specific objective of this work include:

(i) A current review of paunch literature and identification of gaps in literature.

(ii) Develop a methodology to determine the drying properties and characteristics of paunch;

A standard method for paunch characteristics needs to be developed to allow study into the behavior of paunch and other abattoir waste streams. This will allow future studies to build upon the knowledge gained and create a consistent approach to characterise abattoir waste, determine suitable product handling/treatment techniques, and allow evaluation of future implemented treatment methods.

(iii) Determine the optimum paunch drying conditions.

Experimentally determined drying rates and equilibrium moisture contents are needed to allow suitable drying technology to be selected and evaluated.

(iv) Recommendations on the optimum drying conditions for paunch waste based on the inherent properties of paunch and future research suggestions.

4.0 Methodology

4.1 Characterisation of Paunch Waste Methodology

The methodology presented in sections 4.2, 4.3 and 4.4 provides an outline of the methodology developed for characterising paunch in terms of drying rates, equilibrium moisture content and calorific value (energy content). The drying rates will identify what conditions are optimum for fastest drying to enable dryer design selection. Equilibrium moisture content will inform the limit of drying and calorific value will inform the expected energy output from paunch.

4.2 Sample Collection and Preparation

As there is no standard for sampling or testing paunch the methodology for obtaining paunch samples was based on the Australian standard guide to sampling of particulate materials (1997). This standard ensures that all particles in the paunch stream have an equal chance of being selected and used in the final analysis. It also includes ways to eliminate bias by using good handling techniques such as eliminating sample contamination and not changing the samples moisture content during collection.

During sampling operator safety is important. Do not place any body part within equipment (e.g. contra shear screens, screw presses), make sure full access to the complete paunch stream is available, collect paunch sample as close as possible to the discharge point without visually segregating the sample. Collect the sample using a bucket or ladle type container. Pass it perpendicular across the full width of the paunch stream at as uniform a rate as possible with alternate directions used for each sample. Then place the sample in an airtight container with the date and sample number written on the container. Where possible obtain data on the finishing procedure used on the cattle during the week prior to slaughter (e.g. grass or grain fed cattle).

The best practice for the preparation of the paunch samples was based on the Australian standard guide part 2: preparation of samples (1997) with the aim being to keep the properties of the test samples the same as the original sample. All surfaces that the paunch comes into contact with should be abrasion-resistant to avoid contamination, corrosion-resistant trays should be used for drying, and no reduction of the sample should be carried out on samples that are to be used for particle size and/or bulk density determination. To reduce sample division errors the paunch sample should be manually mixed before any sample division takes place. Dust contamination is controlled in the sample collection by placing the paunch sample in an air tight container and in sample preparation by performing all handling, tests and analysis in a dust free laboratory. All equipment should be cleaned between tests to eliminate sample cross-contamination. Samples divided for chemical analysis must have a mass greater than 50 grams. These guidelines ensure that test results will be representative of the original sample.

Once the sample has been collected and prepared for testing at least two samples should be placed in a moisture balance for initial moisture content determination. Samples should also be classified as either predominantly grass or grain type paunches. This can be determined visually based on the particle size and shape of the paunch. Figure 1 shows a predominantly grass and a predominantly grain type paunch. Grass paunches display thin rectangular particles (and consist of roughage type feed such as grass or hay) while predominantly grain type paunches display thin rectangular particles (as per the grass type paunch) mixed with a variety of possible shapes such as round or elliptical particles. The grain type paunch will also feel and look grittier than the grass type paunch due to the grain content.

Figure 2- An example of grass (left) and grain (right) type paunches

4.3 Drying Rates and Equilibrium Moisture Content

A thin layer dryer provides valuable drying information that can be used for product characterization, product quality management and evaluation, product drying computer simulation (using the products specific drying constant), selection and performance testing of drying equipment, and for obtaining a products optimum drying temperature and humidity (ASAE Standards 1999).

Thin layer dryers expose a product to constant air flow (generally about 1m/s with a minimum flow of 0.3 m/s), temperature, and relative humidity. The definition of a thin layer being a 'layer of material exposed fully to an airstream during drying. The depth (thickness) of the layer should be uniform and should not exceed three layers of particles' (ASAE Standards 1999). During drying the product weight is measured nearly continuously with a required accuracy of 0.2% of the sample mass. Temperature sensors need an accuracy of ± 1°C, relative humidity needs an accuracy of ± 3%, and air velocity needs an accuracy of ± 5% (ASAE Standards 1999). Having consistent and reliable control over drying conditions is necessary for the accurate quantification of drying parameters. A thin layer dryer is one such way to determine these fundamental parameters.

In a novel approach to create a thin layer dryer an environment chamber was used to produce consistent air conditions with a load cell wired into a custom built data logger used to record changing weight over time. Figure 2 shows the load cell incorporated into a tray holder which is wired into the data logger. Samples were placed inside the environment chamber and left until equilibrium moisture content was achieved. The data obtained was then converted into moisture content for use in the drying equations.

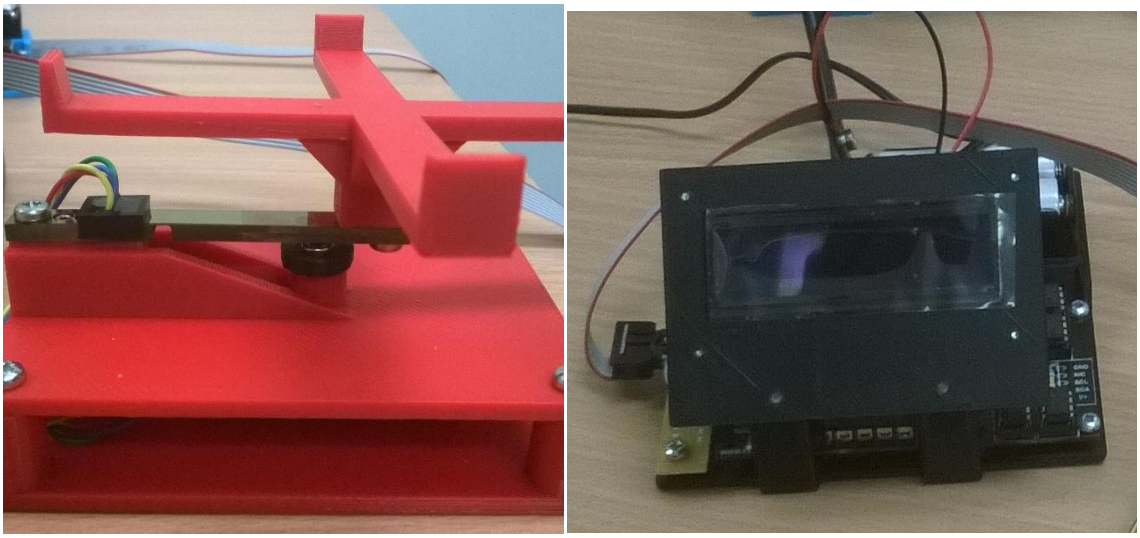

Figure 3 - Load cell incorporated into a tray holder (left) which is wired into the data logger (right)

Drying rate data for drying equations need to be obtained on an apparatus such as a thin layer dryer however equilibrium moisture contents are also needed for determining the moisture ratio and for complete product characterisation. Equilibrium moisture content is easily obtained at the end of a drying run as equilibrium is the final stage of drying. Equilibrium moisture content tells us the minimum moisture content that a substance can be dried to under set drying conditions. Equilibrium is met when the rate of evaporation equals the rate of condensing of a substance. Equilibrium moisture content is important in terms of drying in that once it has been reached; no further drying is possible at those conditions. Equilibrium is found during the drying run once there is no longer any change in weight of the sample. Figure 3 demonstrates the change in weight over time for 35°C temperature with 40% relative humidity. The graph shows the load cell maintained accuracy and shows an expected plateau around 15g where equilibrium was met.

The equilibrium moisture content of paunch waste will benefit future studies by providing storage information, drying limits, and values to be used in drying equations such as calculating the moisture ratio. Moisture ratios are calculated:

$$MR = \frac{(MC - MC_{e)}}{(MC_i - MC_{e)}};$$

Where MR is the moisture ratio, MC is the final moisture content, MC_i is the initial moisture content, and MC_e is the equilibrium moisture content. This calculation allows comparison between differing initial moisture contents.

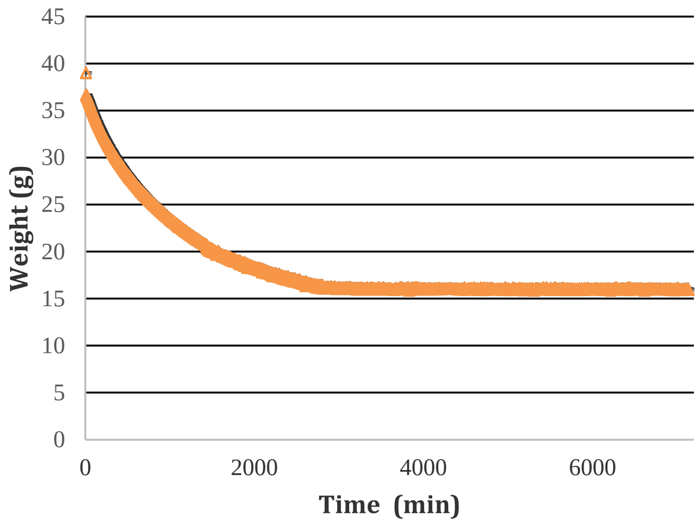

Figure 4- Weight (g) versus time (mins) for 35°C temperature and 40% relative humidity

Average drying rates used for comparison are based on Farmer, Farouk and Brusewitz's (1980) equation for an average daily drying rate which is given by:

$MC = MC_i - ADR \times T$;

Where MC is the final moisture content, MC_i is the initial moisture content, ADR is the average daily drying rate, T is time.

4.4 Energy Content

Oxygen bomb calorimetry is a relatively cheap yet reliable method to determine the gross heat of combustion (calorific value) of a product. A bomb calorimeter measures heat changes at constant volume.

The oxygen bomb should be calibrated with a standard benzoic acid sample for each set of tests and the energy equivalent of the calorimeter calculated. The change in temperature is recorded as is the mass of the sample. These are used to calculate the gross heat of combustion (calorific value) of the sample.

The energy equivalent of the calorimeter is:

$$W = \frac{m * H_c}{\Delta T};$$

Where W is energy equivalent of calorimeter, m is mass, Hc is heat of combustion of Benzoic acid, ΔT is the change in temperature.

The gross caloric value of the sample is then calculated by:

$$H_g = \frac{\Delta T * W}{m};$$

Where Hg is the gross heat of combustion, ΔT is the change in temperature, W is the energy equivalent of the calorimeter, m is the mass.

5.0 Project Outcomes

Thin layer drying rates, equilibrium moisture content and calorific values were calculated for paunch waste acquired from two abattoirs in south east Queensland.

5.1 Drying Rates – Thin Layer

Thin layer drying was used to determine average drying rates of paunch as thin layer drying is the 'best case' drying time achievable for a product. Thin layer drying allows determination of how a product will react under certain drying conditions. The paunch was classified as either predominantly grass or grain and each test was run in duplicate using two load cells (average time for one test roughly one week). The average drying rate for 35, 45, 55°C air with humidities 40, 60, and 80% can be seen in figures 4, 5, 6. These show an expected trend in the decline of drying rates as the humidity is increased.

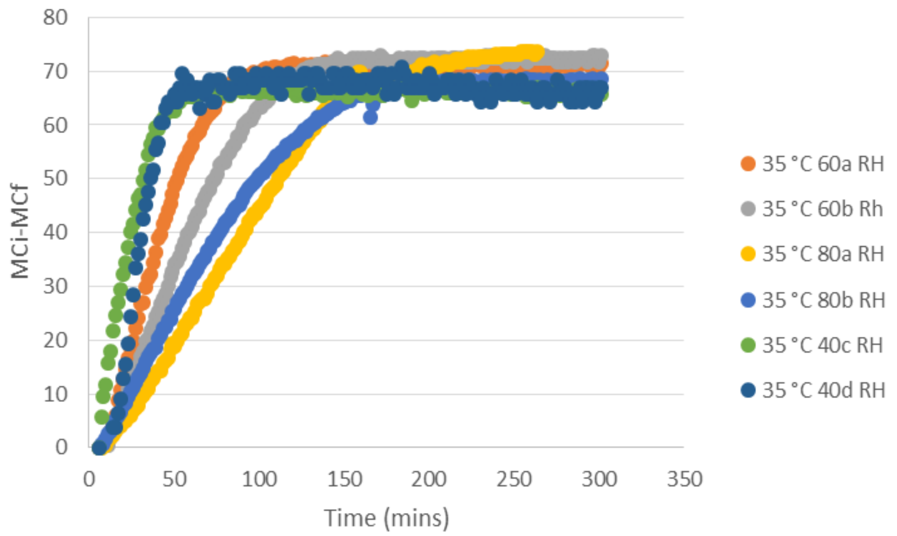

Figure 5- 35°C air temperature with 40, 60, 80% relative humidity.

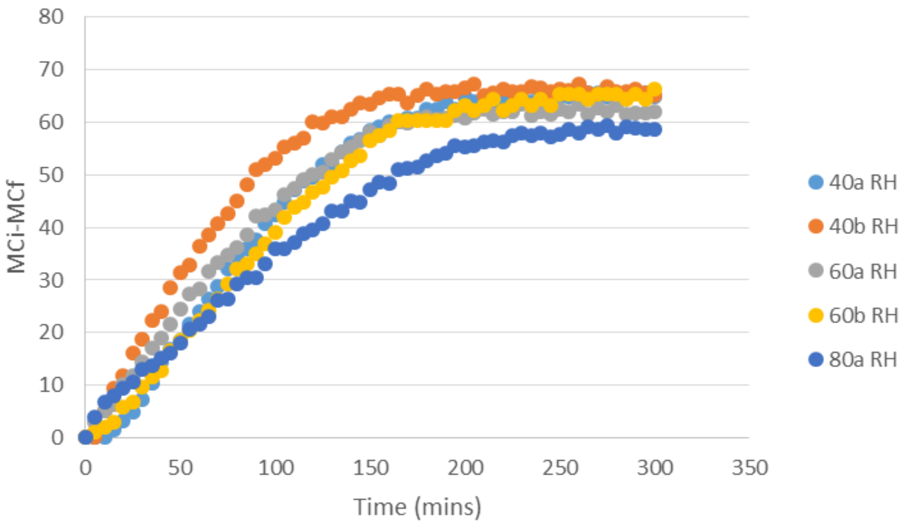

Figure 6 - 45°C air temperature with 40, 60, 80% relative humidity.

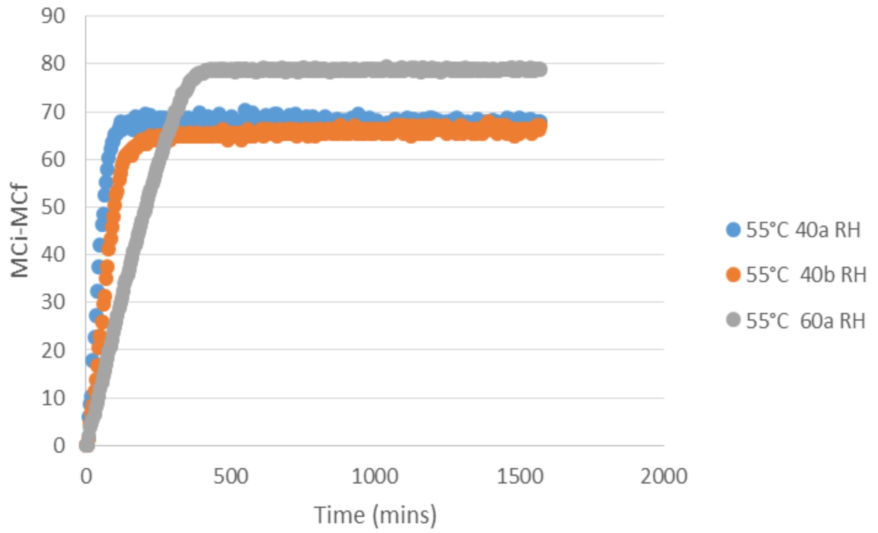

Figure 7- 55°C air temperature with 40, 60% relative humidity.

Figure 7 graphically represents all three temperature ranges at varying humidities. This graph shows some unexpected possible groupings of equal humidity at varying temperature. The equal humidity lines were therefore graphed for varying temperature (figures 8, 9 10).

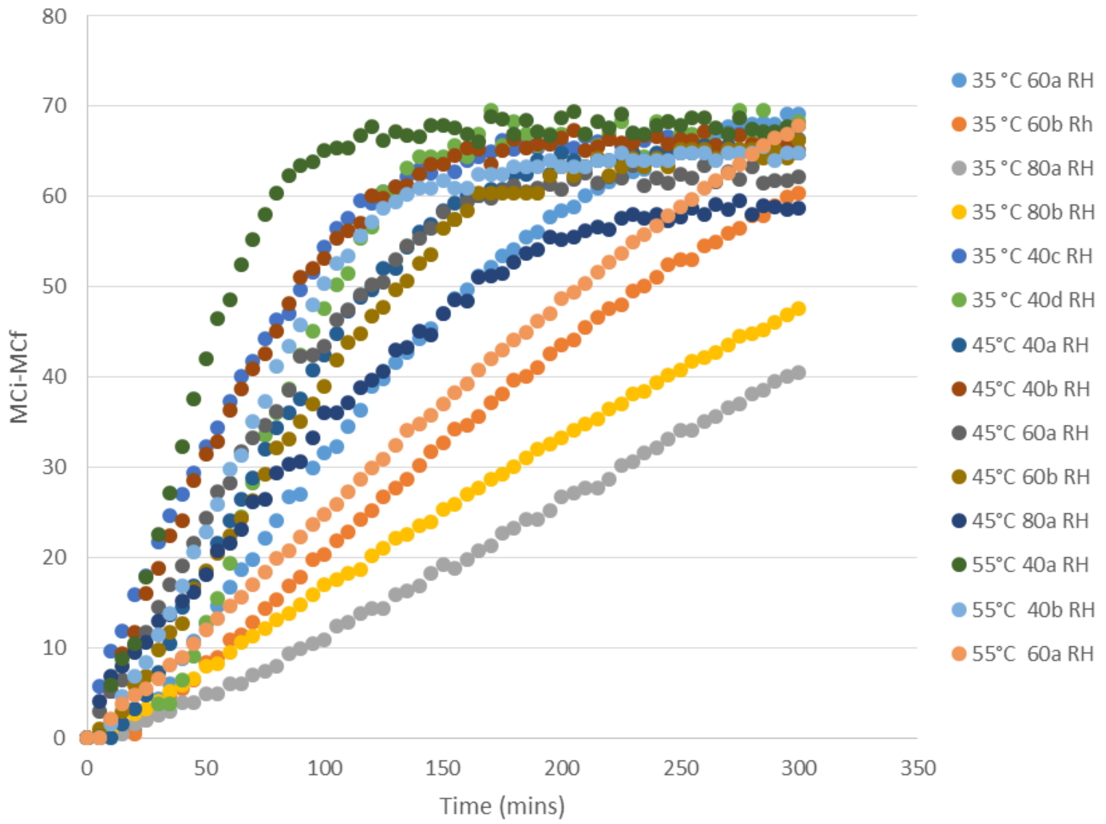

Figure 8- Graphical representation of all three temperatures (35, 45, 55°C) at varying humidity.

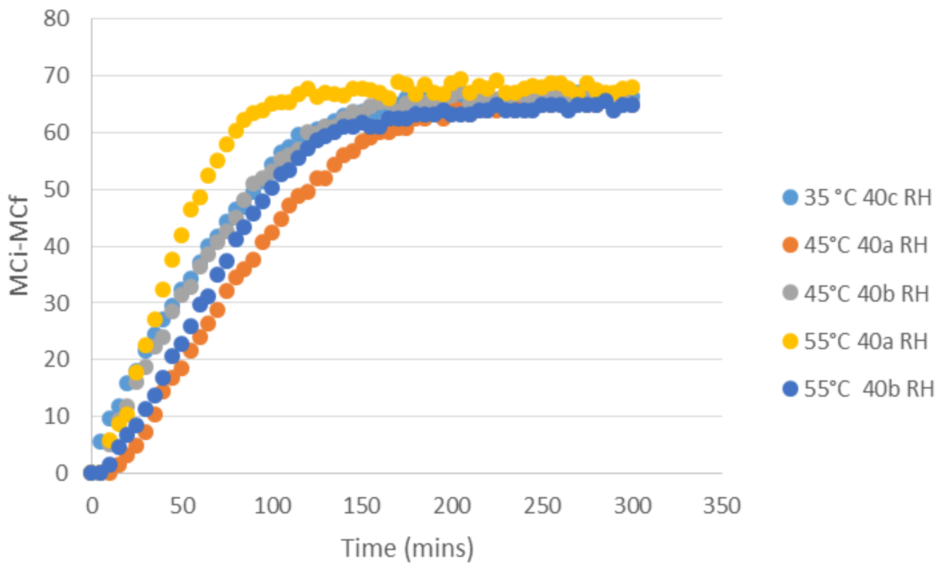

Figure 9 - 40 % relative humidity with 35, 45, 55°C temperature.

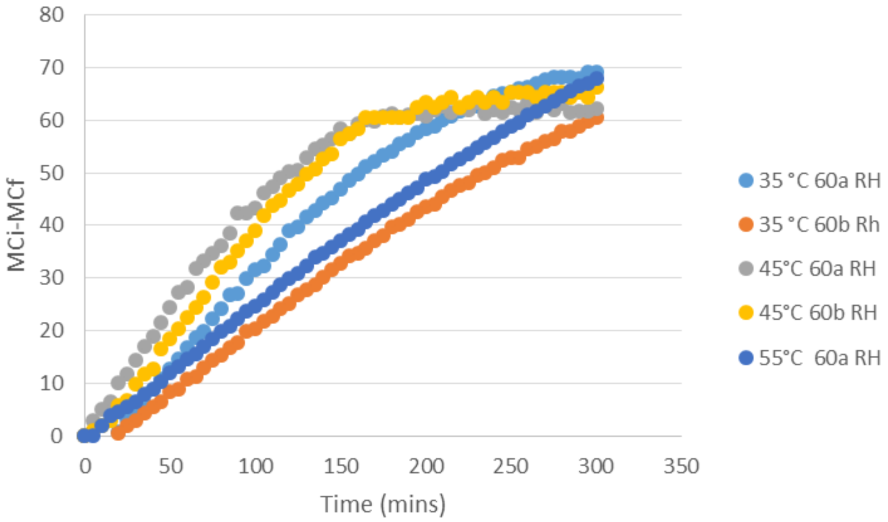

Figure 10 - 60% relative humidity with 35, 45, 55°C temperature.

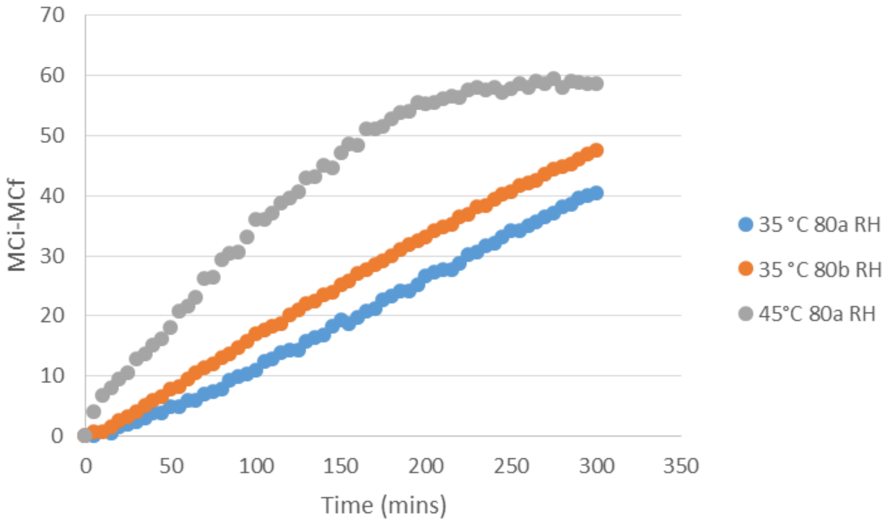

Figure 11 - 80% relative humidity with 35, 45°C temperature.

The average drying rates for 35, 45, and 55°C air temperature with relative humidities of 40, 60, and 80 % were determined and are summarized in table 1. Table 1 shows a consistent decline in drying rates as the humidity is increased for each temperature. The type classification of paunch in the table was further clarified to include grain/grass. These were more of a mixed type paunch as opposed to the predominantly grass or grain type paunches.

Table 2: Average drying rates for 35, 45, 55°C air temperature with 40, 60, 80% relative humidity (grain/grass was a more mixed type paunch compared to the predominantly grass or grain type paunches)

Temperature °C	Relative Humidity %	Average Drying Rates % per minute (w.b)	R squared	type
35	40	0.45	0.9	grass
35	60	0.25	0.99	grain
35	80	0.15	0.99	grain/grass
45	40	0.44	0.95	grass
45	60	0.41	0.99	grass
45	80	0.34	0.98	grain/grass
55	40	0.78	0.98	grass
		0.48	0.97	grain/grass
55	60	0.25	0.99	grain

5.2 Equilibrium moisture content

Equilibrium moisture content was calculated at the end of each drying run once no further change in weight occurred. Grass and grain samples were averaged together as there was only a slight variation between grass and grain equilibrium moisture content as seen in the standard deviation between samples.

Table 3: Averaged equilibrium moisture content values (% wet basis)

Averaged Equilibrium Moisture Content (% w.b)						
	Relative humidity					
Temperature °C	**40%**	**Std dev**	**60%**	**Std dev**	**80%**	**Std dev**
35	7.998	0.19	10.84	0.08	13.44	0.45
45	7.935	0.02	9.595	0.36	13.12	0.52
55	7.135	0.12	9.434	0.30		

5.3 Energy Content

Paunch was collected from two abattoirs in south- east Queensland and separated into predominantly grass or grain type paunches. These were dried and particle size reduced if large grain particles were present. This was done to reduce incomplete combustion of the samples in the bomb. All samples used for calculations were completely combusted with no sample residue left in bomb. An XRY – 1A Oxygen Bomb Calorimeter was used and calibrated using Benzoic acid one gram pellets (Parr instrument Co., USA). To account for variation in the paunch the standard deviation of the energy content values were taken for both grass and grain type paunches. The average gross calorific value for grass type paunches is 17.3 MJ/kg with a standard deviation of 0.483, grain type paunches is 20.2 MJ/kg with a standard deviation of 0.678. The standard deviation between the types is 1.917 which shows a significant difference between grass and grain type paunch energy content.

6.0 Discussion

6.1 Drying Rates – Thin Layer

Drying rates were determined for 35, 45, and 55°C air temperature at 40, 60, and 80% relative humidity. In accordance with drying theory the drying rates show an expected drop in rate as humidity increased.

Paunch type appeared to have a significant impact on drying time. The difference in slopes of the same temperature and humidity lines could be explained by the difference between grass or grain type paunches and variation in and between samples. This was demonstrated in the significant difference in the slopes belonging to the 55°C 40% drying rate which were 0.78 % per minute for grass and 0.48 % per minute for grain/grass. This would appear to be consistent with the findings of Griffith and Brusewitz (1980) that the drying time for grain type paunches can be up to five times longer than grass type paunches. This is likely due to the second stage (internal moisture migration) of drying where the moisture in the grain particles in the paunch have a longer path length to travel to the surface of the grain to allow evaporation than the grass particles.

Variation in both grass and grain type paunch drying rates is expected due the large variability in the samples. The 55°C 60% RH line demonstrated variation between samples as it appears to differ from the other graphed data lines. However, this 'difference' was due to an unusually high initial moisture content and a much more yellow/green liquid in the sample than other acquired samples. This variation in paunch composition is expected due to the large variation in cattle finishing procedures and the types of feed used. Variation is also due to the different treatment methods implemented at abattoirs for separating the liquid from the solid paunch waste such as screw presses and contra shear screens. These dewatering methods impact the initial moisture content of the sample which thus affects the drying time.

However, some unexpected results were also observed. There appears to be a larger than expected effect on drying due to relative humidity. While there was an overall trend in faster drying rates for lower humidity there appeared to be less distinction between temperatures. The fastest drying rate belonged to the 55°C 40% climatic conditions with the 35° 80% conditions having the slowest drying rate. Although the difference between temperatures does not appear to significantly reduce the drying time as opposed to the effect of humidity, paunch type, and dewatering method.

There is no control on the type or variation of paunch that will be need to be dried at an abattoir. However, a few factors must be considered to optimize dryer design. In terms of drying paunch with a suitable dryer, such as a solar dryer, less importance should be placed on the absorber (temperature achievable) as on the dryers' ability to control relative humidity. The drying rates show that theoretically a dryer that could reach 55 degrees in summer and only 35 degrees in months (or on days) with less solar insolation should perform relatively similarly as long as humidity is controlled (such as condensation inside the dryer). The thin layer drying rates compared to the drying times achieved by other methods (one week to sun dry, 5 days in a modified solar still (eds Witherow & Scaief 1976, Bridle 2011, Farmer, Farouk, & Brusewitz 1980)) demonstrates the importance of the chamber design. The more surface area of the paunch exposed to the drying air will significantly reduce drying time. Solar stills can suffer from condensation problems as can most solar dryer designs. Solar dryer design selection should focus on designs that have incorporated solutions to this problem such as condensation collectors.

6.2 Equilibrium moisture content

Equilibrium moisture content tells us the minimum moisture content that a substance can be dried to under set drying conditions. This means that once equilibrium with the surrounding air has been met not further drying is possible. For example, 13.44% MC is the lowest possible MC for 35°C and 40% RH drying conditions (as shown in Table 2).

Table 2 shows that a reduction in humidity had a greater effect on reducing the equilibrium moisture content than increasing the temperature. Equilibrium appears to range between 7 to 13 % MC for humidities 40 to 80% in the temperature range of 35 to 55°C.

Dried paunch storage will be affected by equilibrium moisture content as a product will always try to reach equilibrium in any environment. Therefore, if the paunch is stored in a high humidity environment the moisture content will increase. In addition knowing the limit to drying at certain conditions will benefit future equipment drying designs and end uses.

6.1.3 Energy Content

The standard for the energy content of paunch has been 16.7 MJ/kg (Ricci 1977). This value is comparable to the obtained grass type paunch value of 17.3 MJ/kg. However, there was a significant difference found in the calorific value for grain type paunches of 20.2 MJ/kg. Compared to other gross caloric values of commonly used fuels paunch shows a viable energy content with only bituminous coal having a higher heating value (HHV) than grain type paunches as shown in Table 3.For mixed type paunches the energy content will be between 17.3 – 20.2 MJ/kg. These values demonstrate paunch as a potentially useful waste to energy stream.

Table 4: Gross calorific values of paunch and other commonly used energy sources

COMPARISON GROSS CALORIFIC VALUES		
Type	**HHV (MJ/kg)**	**Reference**
Black coal QLD	28.69	Coal analysis Dec 2015 (Spence, M 2016, pers. comm., 9 May)
Bituminous coal	34.89	Higgins & Elonka 1976
Wood	16-21	Stout 1983, eds. Rosilla-calle et.al 2007, Higgins & Elonka 1976
Corn cob	18.6	Stout 1983
Lignite coal	16.28-18.6	Higgins & Elonka 1976
Sawdust	18.14	Demirbas 2003
Wheat straw	17.51	Demirbas 2003
Paunch (grass - grain)	**17.3 – 20.2**	Spence 2016
Cotton gin	15.5	Demirbas 2003
Rice husk	13.524	Demirbas 2003

In reality the gross calorific value (or higher heating value) is not achievable. Moisture content of a sample needs to be taken into account due to the energy required to remove the moisture before combustion. The equilibrium moisture content values show that under certain conditions bone dry paunch is not possible. Therefore, the lower heating value (LHV) is measured by subtracting the latent heat of vaporization of water from the HHV:

$$LHV = \text{HHV}(1-\text{M}) - 2.447\text{M};$$

where LHV is the lower heating value MJ/kg, HHV is the higher heating value MJ/kg, M is the wet basis moisture content in decimal, 2.447 is the latent heat of vaporization of water MJ/kg (Sokhansanj 2011).

For example: equilibrium moisture content for 35°C air temperature at 40% relative humidity is 7.998%. Using the energy content of grain type paunches of 20.2 MJ/kg the LHV is 18.39 MJ/kg.

Assuming a medium sized abattoir produces 100 m3 of paunch per week at 75% initial moisture content then 33 m3 of paunch is produced per week at 7.998% EMC, this equates to 1 716 m3 per year (assuming 52 week operating period).

The coal value obtained from an abattoir in south east Queensland has a HHV of 28.69 MJ/kg at 3.3% MC with a LHV of 27.66 MJ/kg. The same medium sized abattoir uses approx. 2200 Tonne of coal per year.

Possible paunch energy = 1 716 000 kg/year x 18.39 MJ/kg (LHV) = 31 557 240 MJ per year

Possible coal energy = 2200 000 kg/year x 27.66 MJ/kg (LHV) = 60 852 000 MJ per year

This shows paunch has the potential to provide approximately 50% of the energy needed from coal use. However, a more detailed scenario needs to be calculated as the moisture content of coal is generally increased before use in the boiler (this would affect the LHV). It may be possible to use the higher moisture content of paunch as the rewetting agent in this case and new calculations made in regards to the actual achievable energy.

The mixing ratio of two products for a set overall moisture content can be solved for the mass of the second product:

$$m_2 = \frac{(m_1 \times G) - (m_1 \times MC_1)}{MC_2 - G};$$

where m is the mass kg, G is the goal moisture content %, MC is the products moisture content %. Note that the moisture goal must be between the moisture contents of the two materials being mixed (Trautmann & Richard 1996).

If the goal moisture content (G) is 9% for use in the boiler, mass of paunch (m_1) per week is 38 440 kg per week at a moisture content of 13.44%, coal moisture content (MC_2) is 3.3%.

$$m_2 = \frac{(38440 \times 9) - (38440 \times 13.44)}{3.3 - 9};$$

Mass of coal per week to be mixed with paunch = 29 943 kg to 38 440 kg of paunch or a **1:1.3** mix for above moisture contents.

The above energy and mix ratio calculations show that paunch has the potential to be a significant waste to energy stream for the red meat industry to implement.

7.0 Conclusions/ Recommendations

Drying rates were determined for 35, 45, and 55°C air temperature at 40, 60, and 80% relative humidity. The drying rates showed an expected drop in rate as humidity increased with paunch type, variability, and humidity appearing to have a significant impact on drying time. As there is no control over the type or variation of paunch to be dried the main focus of a dryer design should be on its ability to control relative humidity (eg possibly an active solar dryer using fans to reduce condensation and increased humidity inside the dryer) as opposed to a focus on temperature. Although it appears that a high temperature, low humidity dryer will be the most efficient design there doesn't appear to be a significant gain in increasing the drying temperature without humidity control.

Equilibrium moisture contents were determined with humidity having a greater effect on the moisture content than temperature. Equilibrium moisture content ranged from approx. 7 to 13 % MC for humidities 40 to 80% in the temperature range of 35 to 55°C. Equilibrium moisture content is the minimum moisture content achievable at certain climatic conditions.

Energy content was determined to be between 17.3 – 20.2 MJ/kg HHV for grass and grain type paunches. This energy content could significantly reduce the coal usage on sites with a coal fired boiler.

7.1 Future directions

Further characteristics of paunch should be found and the field of knowledge increased into the behavior of paunch. A number of interesting paunch behaviors were identified in this report and further comparison of drying rates (for grass and grain type paunches), rates for different depths, and more equilibrium moisture contents would create a robust understanding of this material. Also a more detailed scenario needs to be calculated for using paunch as a rewetting agent for coal to check if the LHV values are affected and then testing results in a boiler.

Solar dryer types need to be evaluated to determine the most effective design. A focus should possibly be on active dryers as opposed to passive dryers and tunnel type dryers over solar still designs. This is due to the ability to control increased humidity inside the dryer due to forced air over the sample as per an active dryer and better control over condensation inside a tunnel dryer as opposed to a modified solar still. Future work into the size of the dryer needed to handle the amount of paunch produced per week and the chamber design to increase the surface area of the product to be exposed to the drying air are also needed.

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Appendix 1

Key papers and technical reports are identified in table 1. This table gives an overview of the available papers on paunch with a brief description of the key findings of the papers. As can be seen from the table there was an interest in paunch as a biomass during the 1970 – 80's which coincided with the first energy crisis. There was then a 30 year lapse in interest due to the end of the first energy crisis until recent renewed interest due to the current second energy crisis. A common theme in the papers is their agreeance that paunch has potential as an energy source as long as there is some form of initial moisture reduction of the paunch waste. Various techniques are discussed for moisture removal with sun drying and solar drying being the most popular method discussed for removing moisture. This is most likely due to the lower cost and environmental benefits of solar drying technology compared to fossil fuel run dryers.

Table 1- Summary of reports on paunch waste characterisation

REPORT	KEY FINDINGS	TECHNOLOGY
Baumann (1971)	Made recommendations to the beef processing industry that all abattoirs should install dehydrators for both blood and paunch with beneficial end uses as a feed additive and reducing wastewater pollution. However, this method would not be economically viable today based on a fossil fuel dryer (Spence 2012)	Gas- fired dehydrator
Eds Witherow and Scaief (1976)	Identified numerous methods for handling paunch.	Gas-fired dehydrator, stockpiling, sun (air) drying, solar drying, presses/ dewatering, incineration, pyrolysis, gasification, co-combustion
Yin and Farmer (as cited in eds Witherow & Scaief 1976)	Claimed to have successfully used air drying to dry paunch to 16 to 20 % moisture content in a week. They turned a 10 cm layer of paunch daily to stop a crust forming along the top. However, sun drying or open air drying (exposing a product to the sun) is not feasible due to the many inherent disadvantages. These disadvantages can be seen in some of the problems encountered by Yin and Farmer in their study such as rain rewetting the paunch, fly and odour problems. These problems were dealt with through the building of a solar still with mechanical agitation as opposed to hand stirring of the paunch.	Sun (air) drying, solar drying
Ricci (1977)	Ricci (1977) set about to design and demonstrate a fluidized bed incineration system to handle the paunch waste stream produced by (beef) abattoirs. At the time of printing (Ricci 1977) it was implied that this design would proceed and results in the implementation be presented in a subsequent report. Data are not readily available to indicate whether this study was successful or to allow investigation into whether it would be economically viable in today's market.	presses/ dewatering, incineration

Farmer, Brusewitz and Moustafa (1979)	Identified that solar dried paunch has the potential to become a fuel source for abattoirs. They modified a simple solar still design to test their hypotheses on drying paunch. Beneficial results from this study were: 'An open mesh tray bottom significantly increases the drying rate. Breaking of the crust on the second or third day increases the condensate production rate. Continued stirring on subsequent days is not necessary (Farmer, Brusewitz & Moustafa 1979, p 224)'.	Solar drying
Griffith and Brusewitz (1980)	The study used a tunnel dryer to determine a paunch drying constant as a function of air relative humidity, material depth, and time after slaughter in order to optimize paunch moisture reduction.	Solar drying
Farmer, Farouk, and Brusewitz (1980)	Using a modified solar still with direct solar energy and solar-regenerated desiccant for low-insolation days found that they could reduce paunch moisture from 80% to 30% in 5 days.	Solar drying
Brusewitz, Moustafa and Farmer (1981)	Claimed that pneumatic dewatering of paunch to remove loosely held moisture could be done with less energy and in a fraction of the time compared to evaporation techniques. Their study showed that dewatering soon after slaughter removed the most amount of liquid and that storage at low temperatures (10°C) resulted in 10 to 50% less water being removed.	Presses/ dewatering
Bridle (2010)	Reviewed waste pyrolysis using paunch and DAF sludge. The study identified that there are potential economic and environmental benefits using abattoir waste for pyrolysis or gasification. However, the report showed that the paunch and DAF sludge would need to be dried to 20% moisture content (80% total solids) or below prior to being used. As moisture contents higher than 20% would require too much energy from the pyrolyser thus producing a poor quality syngas, rendering it uneconomical.	Pyrolysis, gasification
Bridle (2011)	After the previous desktop study Bridle undertook to design a programme to sun dry, characterize, and use paunch and DAF sludge in two systems; Pacific Pyrolysis, and BiGchar gasification.	Pyrolysis, gasification, sun (air) drying
Bridle (2011)	Bridle then undertook an assessment of dewatered paunch for use in a co-combustion boiler.	Presses/ dewatering, co-combustion
Spence (2012)	Performed a renewable energy feasibility study at an abattoir. Paunch was identified as a suitable biomass. Some preliminary drying constants were obtained.	Solar drying, pyrolysis, co-combustion