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Decay Characteristics of Different Types of Straw Used in Straw Bale Building

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Preface

The aim of this thesis is to investigate the ability of different types of cereal plant straw to resist decay.

Proponents of straw bale building claim that bale buildings reduce carbon dioxide emissions in the atmosphere in a number of ways. The carbon contained in straw is locked within the building structure and is therefore not emitted to the atmosphere. Straw bale buildings are also highly energy efficient in terms of both construction inputs and heating once inhabited, thereby saving energy that would otherwise be sourced primarily from fossil fuels. Straw bale buildings are part of a global movement to mitigate global warming through more eco-positive approaches to human development.

In order for straw bale buildings to reduce carbon dioxide emissions, they need to be sustainable – they need to last. Currently, there is some doubt in the building industry regarding the ability of straw bale to resist decay in the long-term, particularly in temperate climates. Therefore, an ancillary aim of this research is to help straw bale builders make more durable buildings by attempting to identify a more rot-resistant type of straw.

The principal source of data to support this research was a series of controlled experiments undertaken on three types of cereal straw (wheat, barley and rice). Relevant academic studies, and information gathered from straw bale builders and farmers, provided secondary sources of data. . In the controlled experiments, samples of straw were exposed to an environment conducive to microbial degradation of organic matter (moist and warm) and various indicators of decay (i.e. gas concentrations, temperature, and odour) were monitored and recorded. Carbon dioxide production was used as a measure of straw decay.

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Abbreviations

Cc	Cubic Centimetre
C	Carbon
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
C ₂ H ₅ OH	Ethanol or C ₂ H ₆ O
Ha	Hectare
H ₂ S	Hydrogen sulphide
HDPE	High density polyethylene
K	Potassium
MC	Moisture Content (dry basis)
Mg	Magnesium
N	Nitrogen
N-P-K	Nitrogen, Phosphorus and Potassium
0/00	per mil (or: per thousand)
O ₂	Oxygen
P	Phosphorus
PET	Polyethylene terephthalate
RH	Relative Humidity
S	Sulphur

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1 Introduction

1.1 The Climate Change Context

The planet is warming and there is 'strong evidence' that this warming is the result of human inputs of carbon dioxide (CO₂) and other gases to the atmosphere (IPCC, 2001). The extent of the impacts of global warming are unclear, however, what is clear is that change is occurring rapidly and possibly irreversibly, with impacts likely to be felt for many generations to come. The speed at which change is occurring is unprecedented: a 3⁰C rise in global temperature is expected over the next century (Hansen, 2006). In this context, straw bale construction may offer a number of advantages over more conventional building techniques. Straw bale buildings not only help to mitigate climate change by reducing carbon emissions, but also provide versatile, insulative shelter in the face of unpredictable weather patterns.

1.1.1 The Carbon Cost of Building

CO₂ emitted by humans is primarily from the burning of fossil fuels in industrialised nations. Today, CO₂ emissions in industrialised countries come from: industry (32%), transport (30%), agriculture (3%) and buildings (35%) (Price *et al*, 1999, p14). As our largest area of CO₂ emission, the building sector warrants research in finding ways of reducing gas emissions. Buildings create CO₂ emissions in two ways. Firstly, through the construction of buildings, which accounts for 11% of the total global CO₂ emitted (Guy, 2004). Secondly, buildings emit CO₂ through the energy inputs required for heating, cooling, operations and maintenance during the life of the building. CO₂ emissions would be reduced if buildings were designed to last longer, reducing the need for replacement, and designed for greater energy efficiency. Straw bale construction offers several advantages: first, during growth, straw captures CO₂, which is essentially sequestered in bales in a building. As a result straw bale can result in low carbon or possible carbon negative buildings (Mac Math, 2000, p4; Wihan, 2007). Secondly, straw bale buildings are energy efficient. Straw is highly insulative and enables reduced energy input for heating and cooling for the life of the building, thereby reducing CO₂ emissions associated with energy sources.

1.2 Introduction to Straw

Straw consists of the leaf and stem section of cereal crops (See Chapter 2.1.1) (Quail, 2004). Cereal crops are primarily grown for their grains as a source of food for both humans and livestock. Straw can be used for a variety of purposes, but has been an undervalued resource until recently. Often straw has been burnt *in situ*, as a method to return nutrients to the soil and prepare the land for next season's harvest. Recently, the practise of burning straw has been reduced, due to the air pollution it creates through the release of particulate matter and green house gases into the atmosphere. Whole straw can be worked back into the soil in order to add nutrients for the next crop. However, this often delays the planning of the next crop and poses a financial cost for fuel to run mulching or tilling machinery. If straw is not worked back into the ground or burnt, then it is baled and used for a number of other purposes. Baled straw can be used for livestock as feed and bedding. However, it has limited nutrient value as an animal feed. Straw can be burnt in specifically built incinerators to produce electrical and heat energy. Straw can also be used as a building material. Further processing of straw can form it into a variety of other products; such as stramit, a

straw board product (Stramit, 2008). Straw products that have received further processing do however cost more and have a higher carbon cost to the finished product. Or straw can simply be baled and placed in walls as 'building blocks'.

The use of straw as a building material has many benefits. Currently, the catch phrases of the alternative building industry are low carbon, renewable, energy efficient, low embodied energy, recyclable, and sustainable (Bigland-Prichard, 2005, p50). To an increasing number of people, straw bale buildings are the answer to these building requirements. Straw is available and cheap (Bigland-Prichard, 2005, p53). As a natural material, the straw component of a building can be returned to the soil (composted) at the end of its life, thereby minimising waste disposal to landfill. In addition, straw is non toxic and functions as an excellent sound insulator (Mas & Everbach, 1995, p2879). Straw has tested to be possibly better than many other building materials at resisting earthquake tremors (Ash, *et al*, 2003, p31). The straw bale building process can also be an empowering experience as well as an effective community building tool (Edminster, 1996, p1). For these reasons, straw bale building is growing in popularity throughout the world.

1.2.1 History of Straw Bale Building

The original straw bale buildings were built out of necessity. The people living on the plains of Nebraska, USA in the late 19th century had limited building materials available to them (Jones, 2002, p13). For these people, the invention of the baling machine turned a loose pile of waste into a straw building block (Myhrman & Knox, 1993). The horse drawn baling machine was invented in the North America West in the 1870's and quickly thereafter introduced in the state of Nebraska (Magwood, 2005, p5). The early bale buildings were intended only as temporary shelter; however they are still standing today (Straw Bale Association of Nebraska, 2008). The straw bale buildings that have continued to be habituated and maintained are now over 100 years old (King, 2006, p21).



Figure 1: The Burke House, Alliance, Nebraska, USA; built in 1903.

1.2.2 Contemporary Straw bale Building

Straw bale buildings are now being built all over the world. In western countries, home owners are primarily attracted by the natural and thermal qualities of straw. In eastern countries, the focus tends to be more on the affordability of the construction material (Theis

& Myhrman, 1995, p22; Lerner, 2002, p14). Straw bales are being applied to a myriad of building types in both rural and urban settings, from simple homes to elaborate mansions, for schools, wineries, community halls and commercial offices. Essentially, the straw bale is demonstrating a level of versatility common to many conventional building materials.

Straw bale buildings are a relatively new building material, which has increased in use dramatically over the last 10 years. However, straw has received little research into its strengths and weaknesses. What research that has been completed has been effective at finding solutions to many of the weaknesses of this natural building material. Structural engineers have been conservative with its use, and to date no known structural failures have occurred. Insects and rodents can be attracted while the building is under construction; however, once the straw is sealed within plaster, this largely disappears. In terms of fire resistance, plastered bale walls offer excellent protection. Straw, being lighter and more flexible than conventional building materials, is considered safe during earthquakes. The outstanding question regarding the durability of straw bale buildings is the issue of moisture. What is known is that water must be kept away from straw in order to prevent the onset of decay within the bales.

Straw bale structures are no longer limited to the dry, arid conditions of their origins, but are found throughout the world in a range of climatic zones. The thermal properties of straw bale make it a valuable building technique for cool to cold temperate climates, such as Canada, Northern Europe, and Canada. While the technique has been successfully applied in the continental climate of the North American prairies and the semi-arid southwest of the USA, its track record remains limited in moist climates. Straw bale buildings have only been built in cool wet climates for approximately 10 years. This has not given these buildings a chance to prove themselves; to see if they are able to resist the rot of their straw from microorganisms. There have been reported cases of straw decaying in these moister climates (Canada Mortgage and Housing Corporation, 2000). However, in order to be sustainable, straw bale buildings need to be durable, they need to resist decay. Much energy is invested in the construction of a building and if it needs to be replaced in 20 or 30 years then that is an inefficient use of resources. For a building to be durable it needs to last at least 50 years, preferable 100 years, without major repairs being required.

1.2.3 Decay of Straw Bale Buildings

Decay of straw is highlighted as being the most likely cause for straw destruction over the life of a building (Wihan, 2007). Degradation can occur for a number of reasons. Firstly, poor design can allow excessive quantities of water into the straw. Secondly, incorrect detailing during construction can leave gaps where water can get to the straw. Thirdly, insufficient maintenance over the life of the building can leave cracks which let water into the straw. As can be seen the presence of moisture in large quantities presents a particular challenge to straw, as an organic building material naturally susceptible to rot. If degradation occurs, it can result in the following impacts: 1) structural strength can be threatened (Bigland & Prichard, 2005, p115); 2) loss of insulative ability can occur; 3) fungal spores harmful to human health may enter the building; and 4) repairs and replacement of straw might be required, which is time consuming and expensive.

Evidently, minimising the amount of water entering straw bales will increase the durability of a building. In fact, straw can last thousands of years, under particularly dry conditions (Summers, 2003, p1). The rate of decay is highly dependent on the conditions under which the straw is stored prior to building with it, primarily concerning the moisture content. With proper attention to moisture control, a straw bale building should be able to last as long as any conventional wood framed home (Summers, 2003, p1). However, as the popularity of

straw bale construction grows in wetter climates, the incidences of straw rotting are likely to increase while builders develop their understanding of this alternative building material. If the design, detailing or maintenance schedules of straw bale buildings do not take adequate care to keep excessive moisture from the straw, then short and medium term degradation is possible.

Once straw is exposed to moisture, the last line of defence before degradation occurs will be the straw's inherent resistance to decay. Currently, the construction industry does not have enough understanding of the characteristics of straw bales to adequately assess the potential risk of degradation in buildings (Bigland & Prittard, 2005, p76). With further research into the decay characteristics of straw, the usefulness of straw bales as a building material will be increased. The design of straw bale building needs to 'holt' the inevitable step in the organic degradation process (Grant *et al*, 2005, p18). This is why more research is required to investigate the potential and limitations of using straw as a building material.

1.3 The Current Research

The current research examines differences in the decay characteristics of different types of straw. Three different straws are examined: wheat, barley and rice. The decay characteristics of each of these are compared. When straw decays, microorganisms release CO₂ as a result of the degradation process, therefore CO₂ production (kg CO₂/kg dry straw) was used as a measure of decay in (Summers, *et al*, 2003, p1). Experiments were conducted in a controlled environment in which conditions were created to promote decay. This environment is warmer and wetter than would be expected to be encountered within a straw bale wall. However, it enabled decay to occur within the time limits of this research rather than after years, if at all.

1.3.1 Objectives

The aim of this thesis is to examine the decay characteristics of wheat, barley, and rice straw. This thesis hopes to help straw bale builders in making more durable buildings by potentially identifying a type of straw that is more resistant to rot. A review of current literature suggests that there has been no such comparative research completed, although some research has looked at the causes of decay in straw (Summers, *et al*, 2002; Summers *et al*, 2003; Summers *et al*, 2005).

1.4 Thesis Overview

This thesis describes an experiment-based study that investigated straw decay. This document is composed of five chapters, including the current introductory chapter.

The second chapter provides background information relevant to the study, such as an overview of straw characteristics, cereal crop production, microorganisms, and the mechanisms of straw decay.

Chapter 3 describes the experimental methodology.

Chapter 4 presents the results from the experiments, followed by analyses and discussion. Results from other studies and anecdotal evidence are also provided.

Chapter 5 provides conclusive statements about the results of Chapter 4 and also examines the limitations of this study and recommends future research.

2 Background

This chapter provides background information on straw characteristics, straw production, microbiology relevant to degradation of straw, and the mechanisms of straw decay.

2.1 Straw

Straw is an agricultural by-product of cereal crop production. Cereal crops are strains of grasses (the *Poaceae* family) that are cultivated and harvested for their grain. The seven principal cereals grown in the world are wheat, rice, maize, barley, sorghum, oats and rye. Wheat is the primary cereal of temperate regions. Barley is used for malting, livestock feed and can be grown on land which is not suitable for growing wheat or rice. Rice is the primary cereal of tropical and some temperate regions. Cereals are grown in greater quantities than any other type of crop. 2,270,330,000 tonnes of cereals are produced per year, with the largest producers being China (18%) and the USA (17%) (FOASTAT, 2004). Straws derived from wheat, barley and rice were chosen for this study because together these cereals supply the majority of the world's food and are therefore widely available around the globe. There are other straws produced by cereal crops that were not examined in this study, such as oat, rye, triticale (a hybrid of rye & wheat), and common reed (*Phragmites australis*).

The straw portion of a cereal plant represents about half the yield of the crop by weight. Therefore, with an annual world production of cereal crops at 2,270,330,000 tonnes, there are approximately 1,135,165,000 tonnes of straw produced annually (FOASTAT, 2004). Straw is considered a low value material and even a waste product to many cereal growers.

2.1.1 Straw Morphology

Straw is largely composed of the structural material that provides support to allow a plant to stand erect. Straw consists of the leaf and stem section of cereal crops (Figure 2). The stem provides an avenue of transport for fluids and nutrients. The leaves obtain food energy by performing photosynthesis. Cereal plants are also composed of the head, which consists of a beard and kernal (containing the grain), and the roots, which obtain minerals and water from the soil.

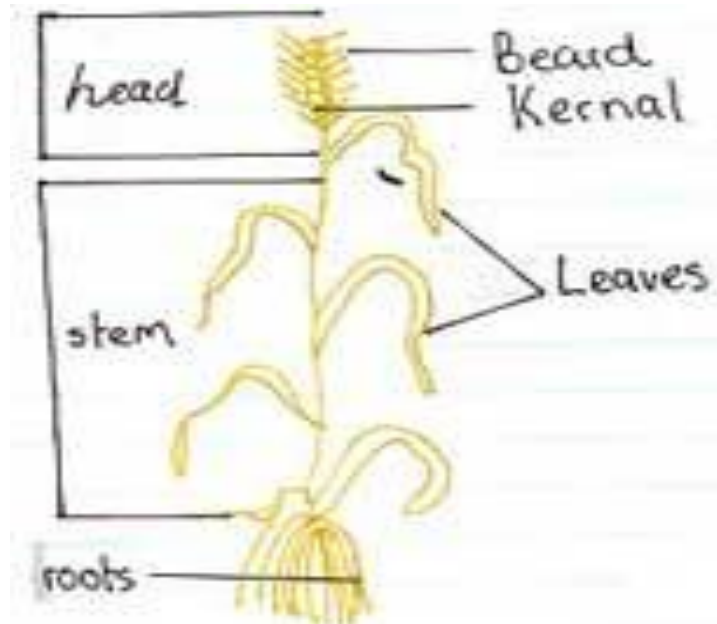


Figure 2: Schematic of a wheat plant, representing a typical cereal crop (Quail, 2004).

2.1.2 Straw Anatomy

A closer look at a typical straw shows a reoccurring pattern of nodal and internodal regions on the plant (Figure 3). The stem consists of nodes spaced apart by internodes. Internodes get progressively further apart as they gain height from the ground. Leaves are generated at the nodes.

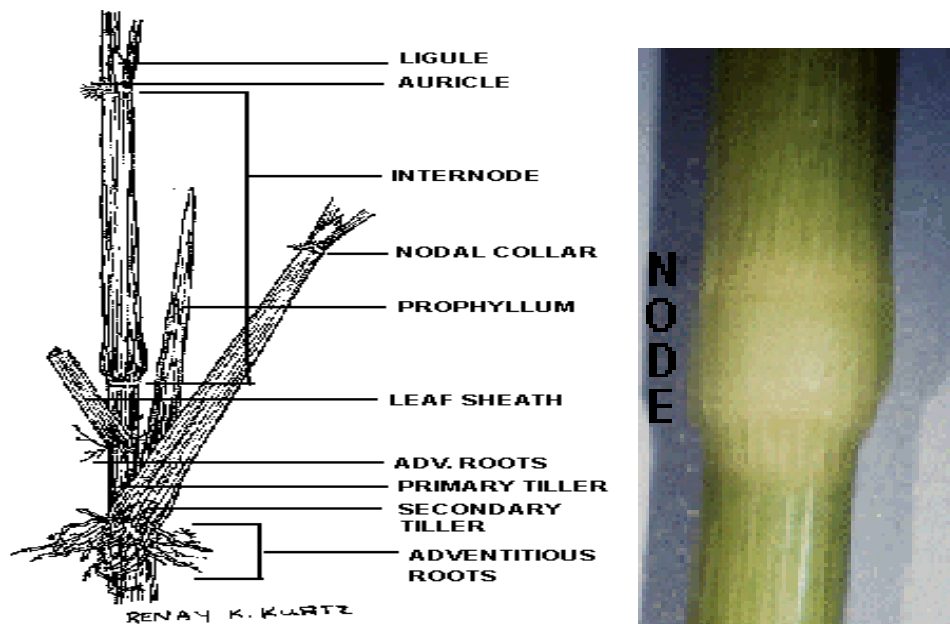


Figure 3: Schematic of a rice plant, including detail of a node on the right (Rost, 1997).

2.1.3 Straw Composition

Straw is composed of 10 % plant material and 90 % air. The plant material consists of cellulose, hemicelluloses, lignin, silica, and water (Butchart, 1994) (Table 1). The fibre structure is made up of cellulose strands bound in a matrix of hemicelluloses, lignin and silica (Summers, 2003, p1).

Cellulose

Cellulose is a complex carbohydrate composed of glucose that forms the main constituent of the cell wall in most plants. Cellulose confers rigidity to plant walls (Bigland & Prichard, 2005, p108) and is hydrophilic.

Hemicellulose

Hemicellulose consists of glucose and sugar. Hemicellulose is less complex than cellulose, but more complex than glucose.

Lignin

Lignin is an integral part of the cell walls of straw. Lignin is a complex polymer and a chief non-carbohydrate in straw and as such is resistant to biological decomposition (Jenkins, 2005, p237). Lignin, which is hydrophobic, is cross-linked with cellulose in the cell wall and forms a type of “cement”. The cross linking within the cellulose by the lignin hardens and strengthens cell walls, creating an obstacle for water absorption through the cell wall. Lignin is resistant to decomposition (Bigland & Prichard, 2005, p108) and can only be decomposed by certain fungi, such as white-rot fungi. Lignin has a very complex chemical structure which slows the rate of microbial breakdown (Lindahl *et al*, 2006, p618). Furthermore, because of its cross-linking with the other cell wall components, it minimizes the accessibility of cellulose and hemicellulose to microbial enzymes, thereby slowing degradation of the straw stalk.

Silica

Silica is an inorganic compound that is absorbed by plants as uncharged silicic acid, (SiOH)₄. Once absorbed, silica is precipitated irreversibly throughout the plant as amorphous silica (SiO₂-nH₂O) (Kobayashi, *et al*, 2006). Plants that absorb silica are called phytoliths. Silica is brought into the plant with water, where it accumulates between the living cells providing structure and natural pest resistance (Summers, 2003, p1). The grass family (*Poaceae*) are phytoliths. The degree to which a plant functions as a phytolith and absorbs silica depends on the growth environment (Archer, 2004). Therefore the amount of silica present in different straws, even of the same cereal type, is variable (The Last Straw, 1993). Rice is a typical phytolith, which accumulates up to 10% silica in the shoot. Silica absorbed by rice has been demonstrated to provide many benefits including improvements in pest and pathogen resistance, heavy-metal tolerance, and rice quality and yield (Kobayashi, *et al*, 2006).

Table 1: Compositions of Straw (Bigland & Prichard, 2005, p108).

Crop	% Cellulose	% Hemicelluloses	% Lignin	% Silica
Wheat	46	31	16	7
Barley	48	32	14	6
Rice	44	27	12	17

2.1.4 Nutrients in Straw

The primary nutrients contained in straw are nitrogen (N), phosphorus (P), and potassium (K) (Table 2). As plants reach maturity, nutrients, particularly N, move from the stem and leaves of cereal crops to the flowering head. As a result, most of the nutrients in a cereal are concentrated in the grain, which is then separated from the remainder of the plant (the straw) during harvest. Nutrient levels in straw vary depending on many factors, such as weather, the type of cereal, seasonal conditions, whether it is a spring or winter crop, and soil condition.

Table 2: Straw nutrient content, as per % of dry matter (USDA, 2008, p1).

Type of Straw	N	P	K
Wheat	0.611	0.064	1.174
Barley	0.683	0.096	1.794
Rice	0.704	0.091	1.477

2.2 Farming Methods for Cereal Crops

In the present study both conventional and organic methods of cereal crop production were examined. In order to profitably grow cereal crops, farmers must manage the environment to create optimum conditions for crop production. This means managing many factors, including water, temperature, and soil condition; economic aspects, such as production costs and labour must also be considered (FAOSTAT, 2008).

Both farming systems attempt to maintain optimum soil nutrients. Each crop consumes nutrients from the soil, which are removed from the farm environment when the crop is harvested. These nutrients must be replaced in the soil in order to avoid a net nutritional deficit, which would affect the growth of future plants. Conventional farming typically applies synthesised inorganic fertiliser to redress the balance of N, P, and K. Organic farms use crop rotation and organic fertilisers, such as compost and manure, to achieve the same result. Both farming systems attempt to minimise crop damage to crops. Conventional farming uses synthetic pesticides and fungicides. Organic farms use crop rotation, companion planting and chemically simple pesticides that break down in the environment quickly.

2.2.1 Conventional Farming

Conventional farming uses high yielding varieties of seed, which have been created to absorb more N. Plants have also been developed to produce shorter stems to more easily carry the heavier grain heads. High yield varieties out-perform traditional varieties if adequate irrigation, pesticides, and fertilisers are used. These are applied at specific stages of plant development, for example fertiliser is applied to wheat at five different times during the growth cycle. Development of new seed varieties, combined with a careful use of fertilisers and pesticides, have resulted in crop yields doubling during the last 50 years.

Fertilisers are chemical compounds applied to plants to improve growth. They typically provide the macro plant nutrients (nitrogen, phosphorus and potassium: N-P-K) or the micro plant nutrients (calcium, magnesium and sulphur) and trace elements, such as iron, manganese, boron, copper, molybdenum, nickel, chlorine and zinc (Table 3, Table 4, Table 5). The total world fertiliser consumption in 2002 was 101,966,074 tonnes (FAOSTAT, 2002). The use of inorganic fertilizer requires careful consideration of the soil's nutrient balance. If excessive fertiliser is applied, there is the risk of the ecosystem being degraded. For example, excess N can leach from fields, causing eutrophication in adjacent water systems. Also, excessive concentrations of trace elements, such as cadmium, uranium and polonium-210 can contaminate the soil, by making the soil toxic to future crops. Potassium nitrate or sodium nitrate, both used as fertilizers, can which show up in water supplies as pollution (Jenkins, 2005, p239).

Pesticides refer to a large number of substances used to kill pests. Monoculture systems using high yielding cereal crops result in an environment conducive to the build up and infestation of pests, and therefore the consequent use of pesticides. Cereal crop production is the second largest user of pesticides, after fruit and vegetable production (Lutz, 1998, p255). A pest can be any living organism that occurs where it is not wanted, for example where it causes damage to crops or humans or other animals. Examples include insects, mice and other animals, unwanted plants (weeds), fungi and microorganisms such as bacteria and viruses. The term pesticide also applies to herbicides, and various other substances used to control pests (EPA, 2008). Selective herbicides kill specific target plants while leaving the desired crop relatively unharmed. Synthetic organic herbicides account for 70% of all agricultural pesticide use.

Plant Growth Regulator is normally applied before or alongside seeding of a crop. Plant growth regulators (PGR) are significant because these are chemical treatments that reduce stem growth and thereby enable the plant to resist lodging (collapse due to rough weather and the weight of a heavy ear of grain). PGR is primarily used on the high yielding varieties of crops because of the larger head of grain.

Table 3: Recommended quantities of N for conventionally grown cereal crops (kg/ha) (IFIA, 1992; DEFRA, 2008b).

Crop Type	Recommending Organisation	
	International Fertiliser Industry Association	DEFRA
Wheat	129-187	0-160
Barley	100-120	0-160
Rice	75-170	<i>Not Applicable</i>

Table 4: Recommended quantities of P for conventionally grown cereal crops (kg/ha) (IFIA, 1992; DEFRA, 2008b).

Crop Type	Recommending Organisation	
	International Fertiliser Industry Association	DEFRA
Wheat	55-58	0-120
Barley	33-120	0-105
Rice	28-122	<i>Not Applicable</i>

Table 5: Recommended quantities of K for conventionally grown cereal crops (kg/ha) (DEFRA, 2008b).

Crop Type	Recommending Organisation	
	International Fertiliser Industry Association	DEFRA
Wheat	125-252	0-145
Barley	33-217	0-145
Rice	0-170	<i>Not Applicable</i>

2.2.2 Organic Farming

Organic farming describes a 'whole system' approach to farming and food production. It recognises the close interrelationships between all parts of the production system from the soil to the consumer (Soil Association, 2008). Organic farming has minimal reliance on outside inputs of nutrients, or substances for weed, pest and disease control and as such is a low input farming system (Holleran *et al*, 2008). The principles of organic farming in the UK can be summarised as: (Soil Association, 2007).

1. Enhance habitat for fauna and flora.
2. Optimise natural processes.
3. Soil use based on nutrient cycling, therefore the use of organic fertilisers where possible, such as manures, worm castings, seaweed and sewage. Inorganic fertiliser use minimised.
4. Use of crop rotation to maintain health of soil.

5. No use of plant growth regulators.
6. Limits on heavy metal concentrations in soil.
7. Use of non chemical pesticides.

The UK Soil association allows four pesticides to be used on certified organic farms; these are sulphur, soft soap, copper and rotenone. These are either of natural origin or simple chemical products that break down in the environment quickly (Soil Association, 2007). Organic herbicides include spices, vinegar, steam, flame and D-limonene (citrus oil). In contrast, non-organic farms have access to 447 pesticides, many of which are highly toxic to organisms in the natural environment (Soil Association, 2007).

The use of traditional varieties of crops may outperform high yielding varieties of cereal if irrigation, pesticides, and fertilisers are not used. This is because traditional varieties have evolved an inherent resistance or adaptability to adverse conditions, such as drought and pests.

2.3 Microorganisms Relevant to Straw Decay

The microbes relative to this study include fungi and bacteria. Microbes (or microorganisms) refer to any organism that cannot be seen by the human eye without magnification (Jenkins, 2005, p239). Microorganisms are numerous and diverse; a teaspoon of grassland soil contains 600-800 million bacteria comprising 10,000 species, plus perhaps 5,000 species of fungi (Jenkins, 2005, p44). A sample of the microorganisms found on rotting plant matter in a compost pile is shown in Figure 4 & Figure 5. As decomposers, microbes play an indispensable role in nutrient cycling, degrading organic matter into inorganic molecules, which can then re-enter plants or other organisms (Lindahl, 2006).

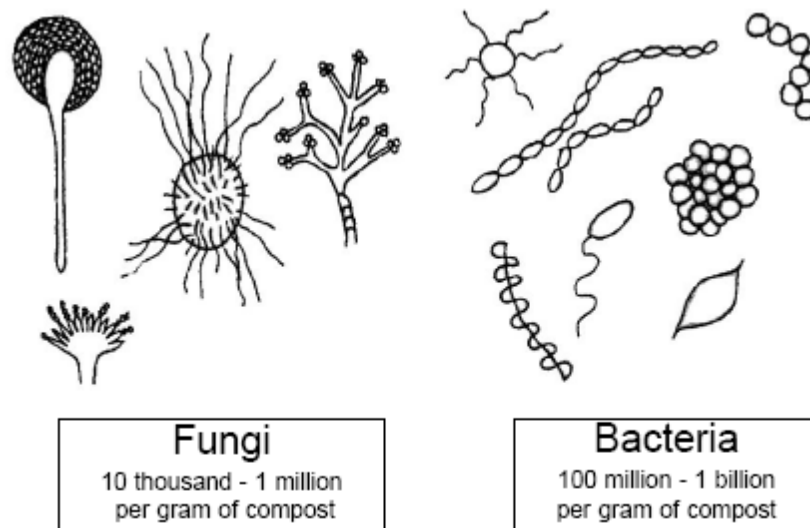


Figure 4: Population comparisons between fungi and bacteria in a compost heap environment; magnified 1000 times (Jenkins, 2005, p39).

Fungi

Aspergillus fumigatus
Humicola grisea
H. insolens
H. lanuginosa
Malbranchea pulchella
Myriococcum thermophilum
Paecilomyces variotti
Papulaspora thermophila
Scytalidium thermophilum
Sporotrichum thermophile

Bacteria

Alcaligenes faecalis
Bacillus brevis
B. circulans complex
B. coagulans type A
B. coagulans type B
B. licheniformis
B. megaterium
B. pumilus
B. sphaericus
B. stearothermophilus
B. subtilis
Clostridium thermocellum
Escherichia coli
Flavobacterium sp.
Pseudomonas sp.
Serratia sp.
Thermus sp.

Source: Palmisano, Anna C. and Barlaz, Morton A. (Eds.) (1996). *Microbiology of Solid Waste*. Pp. 125-127. CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, FL 33431 USA.

Figure 5: Fungi and bacteria typically found in a compost environment (Jenkins, 2005, p39).

2.3.1 Fungi

Fungi are eukaryotes. As eukaryotes, they differ from bacteria in that they contain organelles such as the cell nucleus and mitochondria in their cells. Moulds, a type of fungi, grow as thread like filaments called hyphae (Wichern & Hafeel, 2004, p2). Fungi hyphae are larger and more visible than bacteria (Figure 6). Fungi species that have been found on straw are detailed in below (Table 6, Table 7, and Table 8).

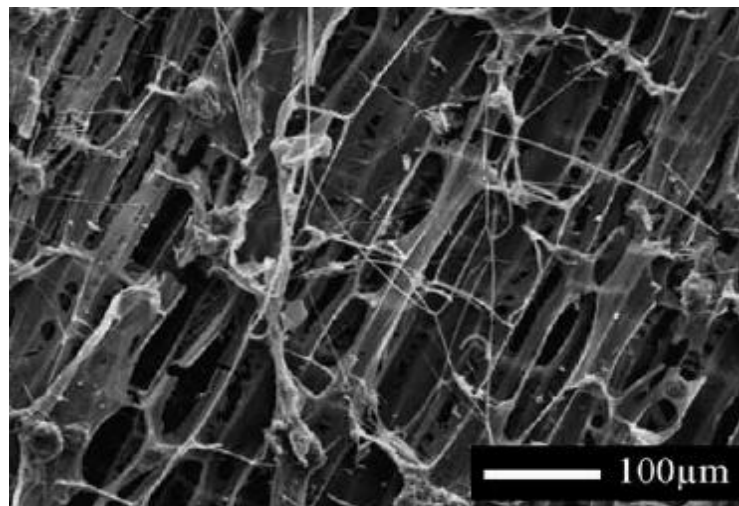


Figure 6: Wheat Straw under a Scanning Electron Microscope after 8 weeks in a compost pile. The fine string-like threads are fungal hyphae and spores in the internal structures of the basal part of the straw (Dresboll & Magid, 2005).

Table 6: Mould species found on samples of pre-harvest, freshly harvested and dry-stored straw (Fog Nielsen, (2002).

Genus	Species
<i>Aspergillus</i>	<i>Glaucus, restrictus, repens, amstelodami, versicolor, candidus, sydowii, ustus</i>
<i>Wallemia (less frequent than Aspergillus)</i>	<i>Sebi</i>
<i>Cladosporium</i>	<i>Cladosporioides, herbarum</i>
<i>Alternaria</i>	<i>Alternate</i>
<i>Aureobasidium (wet conditions only)</i>	<i>Pullulans</i>
<i>Epicoccum (wet conditions only)</i>	<i>Purpurascens</i>

Table 7: Mould species found on samples of stored wet straw (Fog Nielsen (2002).

Genus	Species
<i>Aspergillus</i>	<i>Fumigates</i>
<i>Mucor</i>	<i>Pusillus</i>
<i>Absidia</i>	<i>Ramose</i>
<i>Humicola</i>	<i>Lanuginose, insolens</i>
<i>Chaetonium</i>	<i>Thermophile, globosum</i>

Table 8: Mould species commonly identified within buildings and possibly capable of colonising straw walls (Fog Nielsen, 2002; Bigland & Prichard, 2005).

Genus	Species
<i>Eurotium</i>	<i>Repens</i>
<i>Aspergillus</i>	<i>Sydowii, ustus, versicolor</i>
<i>Penicillium</i>	<i>Brevicompactum, chrysogenum, corylophilum, expansum, polonicum, palitans</i>
<i>Cladosporium</i>	<i>Sphaerospermum, herbarum</i>
<i>Alternaria</i>	<i>Tenuissima</i>
<i>Rhodotorula</i>	<i>Rubra</i>
<i>Stachybotrys</i>	<i>Chartarum</i>
<i>Ulocladium</i>	<i>Chartarum, atrum</i>
<i>Chaetonium</i>	<i>Globusum</i>

The spores of some fungal species can be dormant for up to 50 years (Hawksworth et al, 1995). In marginal conditions, such as low moisture level, conditions need to be maintained for weeks or months before any fungal growth becomes possible (Fog Nielsen, 2005). It has been found that fungi prefer a higher ratio of C than bacteria, therefore fungi often colonise earlier, while cellulose, which contains C is at a high ratio to N (Wichern & Hafeel, 2004, p2)..

2.3.2 Bacteria

Unlike fungi, bacteria are prokaryotes; unicellular organisms and lacking membrane-bound organelles. Typically bacteria are a few micrometres in length and have a wide range of shapes, ranging from spheres to rods and spirals (Figure 7).

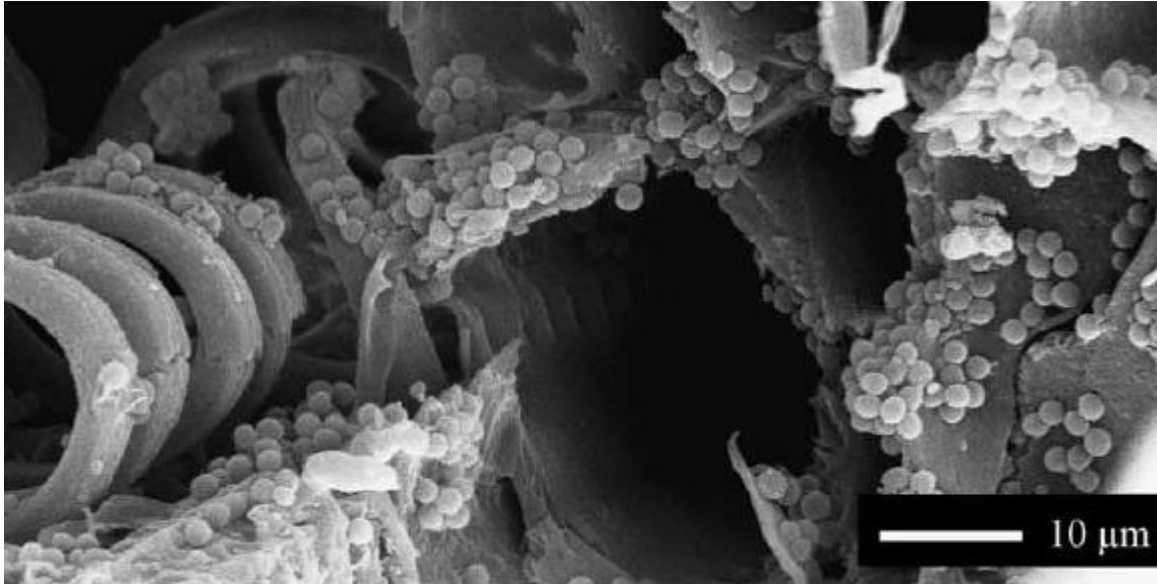


Figure 7: Bacterial colonies covering wheat straw after 8 weeks of composting (Dresboll & Magid, 2005, p6).

2.4 Straw and Water

Water within a straw bale building is dominated by water vapour (Straube, 1998, p4). Cellulosic materials, such as straw have a large internal surface areas and this makes straw hygroscopic. The hygroscopic nature of straw means water vapour or liquid is adsorbed or held by weak chemical bonds to straw (Bigland & Pritchard, 2005, p105; Straube, 1998, p4) (Figure 8). Once straw has adsorbed as much moisture as possible it has reached fibre saturation, this occurs at about 39% moisture content (dry basis) (Bigland & Pritchard, 2005, p109). At that stage, any moisture that has not been adsorbed is accessible to microorganisms. As a result, straw is vulnerable from microorganism decay once it has reached fibre saturation (Wihan, 2007). In fact, due to moisture being unevenly distributed in straw, it would be vulnerable before this point. Microorganisms lack the energy requirements to remove the first layer of adsorbed water molecules, which are firmly hydrogen-bonded to the fibres of the material. However, subsequent layers of moisture are progressively less firmly-bonded; some fungal species are apparently able to utilise some of the more loosely-bonded water molecules (Bigland & Pritchard, 2005, p109). Once straw has reached fibre saturation, then capillary suction or absorption allows moisture to fill pores and cracks on the surface (Straube, 1998, p4).

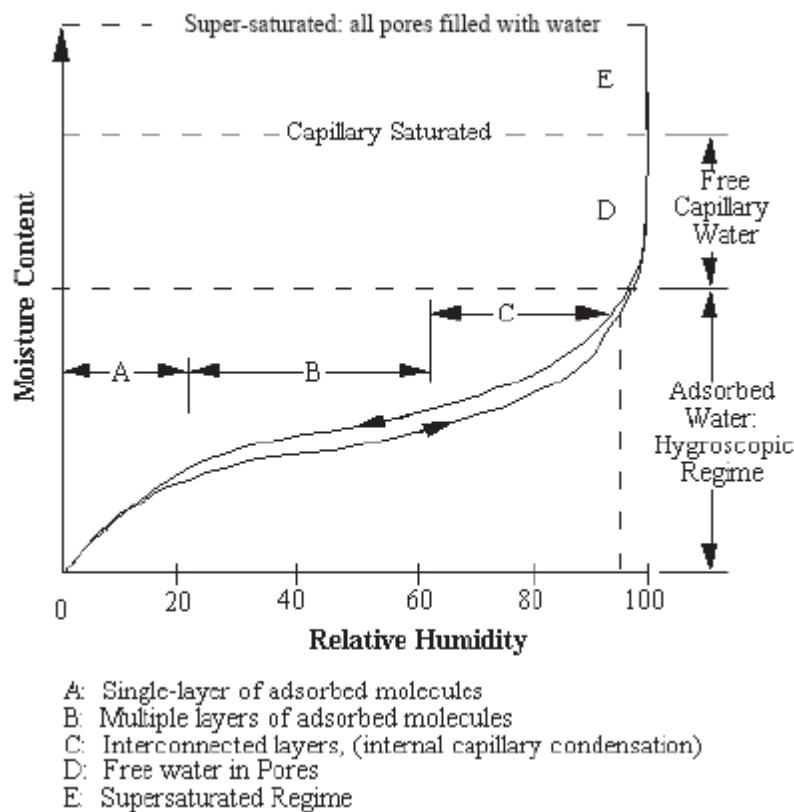


Figure 8: How water is contained within straw; first through adsorption, then capillary action and finally as free water in pores and on the surface (Schwarzmueller, 2004, p15).

2.5 Straw and Decay

When straw decays the organic material in straw is broken down by microscopic organisms or microbes. The spores of microorganisms are baled with straw as it is harvested from the field, and these are ready to reproduce and multiply given the right conditions within a straw bale wall (Summers, 2003, p1). In order for the microorganisms on straw to reproduce the environmental conditions suitable for microorganism activity have to be present. These microorganisms need four things to be present in order to decay straw (Summers, 2003, p1; King, 2005).

1. Oxygen
2. Nutrients
3. Adequate Temperature
4. Sufficient Moisture Content

Oxygen is not seen as a limiting factor in microorganism activity. Straw bales are 90% air, and therefore there is an ample supply of O₂. Although, once activity begins, O₂ will be consumed and the rate that new O₂ can replace used O₂ would be limited by a well plastered straw bale wall (Summers, 2003, p2). Some microorganisms prefer aerobic environments (O₂ rich) and some prefer anaerobic environments (O₂ low). Nutrients are not seen as a limiting factor in microorganism activity (Bigland & Prichard, 2005, p117). Microorganisms require C and N, which are present in straw. Of C, microorganisms will consume cellulose and hemicellulose in preference, however they will also consumer lignin in smaller quantities (Acharyac, 1934, p540). Different straw have different quantities of N and lower quantities of N could slow activity, but not stop it (Bigland & Prichard, 2005, p108).

Straw is lower in nitrogen than what is considered optimum for microorganism degradation. The optimum ratio for carbon to nitrogen for microorganisms is 20:1 to 40:1 where straw has a ratio of 48:1 to 150:1 (Jenkins, 2005, p34; Whatcon County Extension, 2008, p1)(Table 9). If there is too much C, decomposition is slowed and some microorganisms die. Decomposition takes longer when the C: N ratio is above 30. Therefore, high C/N ratio makes materials more durable (Shallow, 2008). The nutrients contained in the straw effect its decomposition. For example, the application of composts and fertilisers affect the balance of carbon and nitrogen in the soil and straw, which affects the ability of microorganisms to decay it (Holzhueter, 2008).

Table 9: C:N ratio of different straws (Jenkins, 2005, p54; Whatcon County Extension, 2008, p1).

Crop	C/N Ratio
Oat Straw	48-60:1
Straw (generally)	80:1
Wheat Straw	80-150:1

Temperature is not seen as a limiting factor in microorganism activity. Temperatures within a straw bale building are at the bottom end of the optimum temperatures that microorganisms thrive in (20-65⁰C) (Jenkins, 2005). Moisture content is seen as a limiting factor in determining microorganism activity (Fog Nielson, 2002, p5; Sedlbaur, 2001, p37). Low moisture content is likely to limit bacteria activity particularly, for they require higher minimum moisture content to be active than fungi. Bacteria generally require a very high moisture content to thrive, however very high moisture content is unlikely to occur (broken water pipe or leak in the roof). Therefore, under normal condition, fungi, which thrive at lower moisture content, are likely to cause much of the decay of straw (Padfield, 2002, p3).

Once the conditions for microbial growth are sustained for enough time, the straw will eventually decompose completely (Wihan, 2007).

2.6 Summary of Chapter 2

This chapter has attempted to detail much of the background information required to understand the processes being undertaken during this study. The next chapter introduces the experimental methodology.

3 Experimental Methodology

The aims of this chapter are firstly, to examine the methodology related to this study. Secondly, to develop a method that achieves the objectives of this study from Chapter 1.

3.1 Method Development

The development of an experimental method to decay straw and measure the rate of decay was based on a method provided by Summers *et al* (2003), with modifications to suit the objectives and limitations of the present study. Summers *et al* looked at straw at a variety of temperatures and moisture contents (MC) and recorded the CO₂ produced as a measure of decay (see Chapter 2). The aims of method development were to create a method that a) accurately measured degradation in straw and, b) generated rapid decay by creating optimum conditions for decomposition. The method chosen to measure decay in straw was by monitoring CO₂ production within a closed system; other methods considered were mass loss, heat generation, changes in C/N ratio and changes in hemicelluloses, cellulose and lignin contents (Dresbol & Magid, 2005, p1). These other methods were not chosen because they required more elaborate laboratory equipment and analysis. By using CO₂ production, it was also hoped to be able to make comparisons between this study and Summers *et al* (2002).

In order to create optimum conditions for straw decomposition the following factors are required: ample nutrients, sufficient oxygen, and an appropriate temperature and MC (see Section 2.3). Both nutrients and oxygen were seen as not limiting factors in decay (Summers *et al* (2003)). The Summers *et al* (2003) study found that a temperature of 30°C and a dry basis moisture content of 160% produced optimum conditions for straw decomposition, as indicated by maximum emissions of CO₂ measured over a period of 140 hours (Summers *et al*, 2003). The present study was focussed on comparing the rates of degradation of different types of straw. Therefore, it was decided that the optimum decay conditions identified by Summers *et al* (2003) would be reproduced for each type of straw in order to observe any differences in maximum CO₂ production.

In the Summers *et al* (2003) experiment, straw samples were cut into 50 mm sections and weighed into plastic (HDPE) containers. 14 grams of dry straw samples per 1.89 litre of container was used. The samples were wetted to a range of moisture contents. The containers had an inlet and exhaust tube placed within them which was connected to a hand held Bacharach CO₂ Analyzer (Model 2820) and an Intoximeters Ethanol Meter (Alco-sensor IV), respectively. The inlet tube was placed directly within the sample and the exhaust tube fed back into the top of the container. The containers were sealed using Teflon hose and latex rubber tubing. The samples were heated to a range of temperatures. The containers were monitored for CO₂ and ethanol concentrations twice daily for a period of 140 hours (see Figure: Diagram of Summers *et al*).

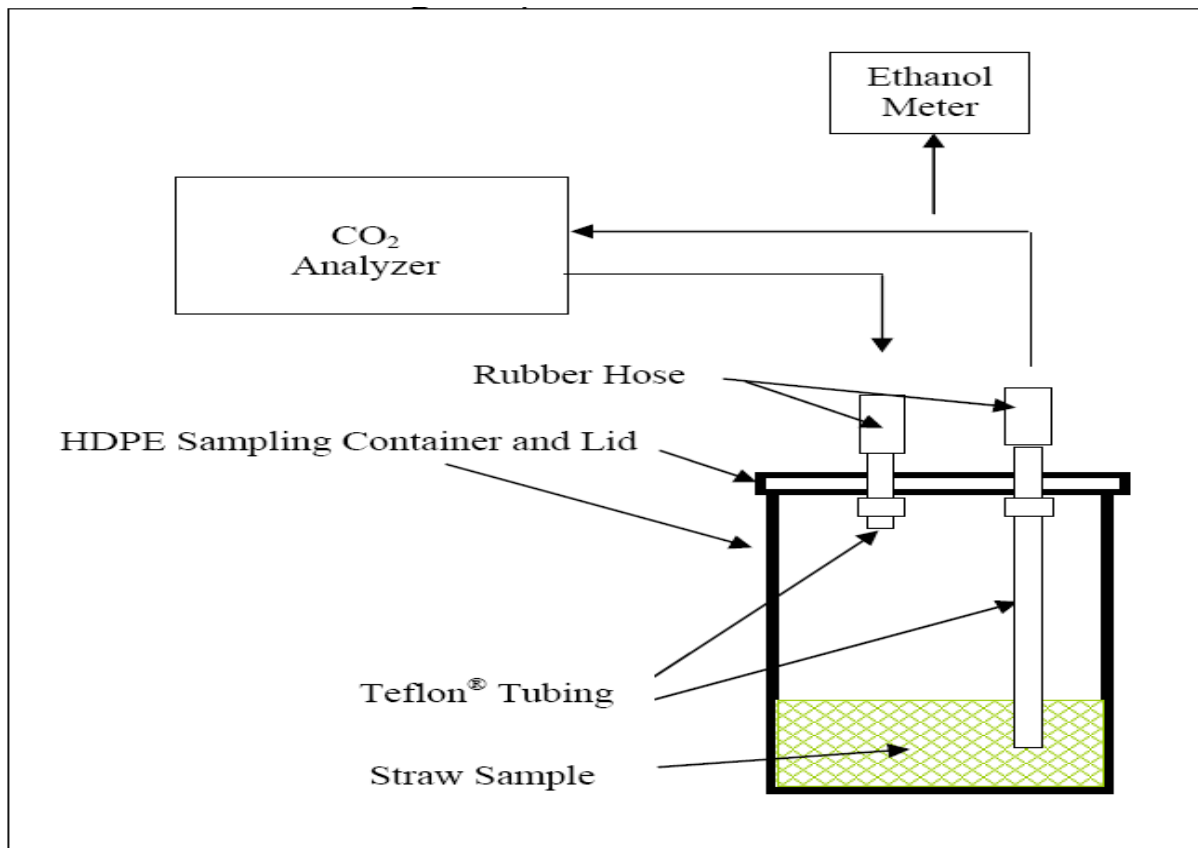


Figure 9: Diagram of Summers *et al* 2003 Experiment (Summers *et al* 2003).

Prior to running pilot studies for this study, the following physical modifications were made to the Summers *et al* (2003) method to accommodate availability of equipment and the specific objectives of the present investigation:

1. GA 2000 gas analyzers were used to record CO₂, O₂, CH₄, H₂S and barometric pressure (see appendix A1).
2. Recordings were taken each hour for 100 hours. 100 hours was chosen because of limited time available. However, recordings were taken more often to show greater detail in the results.
3. The lids were sealed with Teflon tape. Tubing inserted into containers through perforations was sealed using 'No Nonsense Builders Silicone Clear 310ml'.
4. Straw samples were cut into 25 mm sections instead of 50 mm sections. This was done in order to increase the rate of decay by allowing microorganisms increased access to the inner parts of the straw stem which has less resistance to decay (Brandon, 1995, p1).
5. Ethanol concentrations were not recorded. Summers *et al* (2003) found that at temperatures below 35°C ethanol was not a major product of microbial decomposition. Therefore, the measurement of ethanol was deemed unnecessary. Temperatures above 35°C were not considered relative because they are unlikely to be encountered within a straw bale building.
6. A temperature of 30°C and a MC of 160% were used throughout the experiment.

Using the experimental set-up described above, four pilot studies were undertaken. These pilot studies have been summarised in Table X, with further information available in Appendix A3. Figure X depicts Pilot 1 being run, with both GA 2000 gas analyser connected to the one container.

Table 10: Pilot Study Summary

Pilot	Aim	Change	Findings
1	Compare recorded results from the two GA 2000 gas analysers	Both analysers connected to the same container	Near identical results
2	Check for leakage of gas between the inside of the container and the outside atmosphere.	Expired air (breath) put into container and monitored to see if it returned to atmospheric gas concentrations	Return to atmospheric gas concentrations over 87 hours.
2	Minimise gas leakage by using a different type of plastic container	Use of PET (polyethylene terephthalate) plastic instead of HPDE (high density poly-ethylene)).	Increased gas leakage occurred using PET
3	To ascertain that the sample was changing the atmospheric gases in the container	Identical method, although no sample used	No change to gas atmosphere
4	Reduce gas transfer between the inside of the container and the outside atmosphere	Change of silicon sealant used. Also, the use of a plastic bag, sealed over the entire container.	Less gas transfer between inside and outside.

As a result of these four pilot studies, further modifications were made to Summers *et al* approach and an experimental method was developed, as described below.



Figure 10: Pilot 1 located in small residential apartment in Bristol, UK.

3.2 Methodology

This section presents experimental details including the samples used, sample preparation (including moisture content calculation), equipment, and experimental set-up.

3.2.1 Samples

Straw samples were obtained from a variety of farms in the United Kingdom and France during August of 2008. Each sample was carefully labelled on receipt to aid identification. Wheat samples were sourced directly from the farms where they were grown. Barley samples were obtained through straw merchants. Rice samples were supplied by the French National Institute for Agricultural Research. The samples from France were not modified or chemically treated as they passed through customs to enter the United Kingdom. Samples number 2 and 5 were grown to organic guidelines; however they were not certified organically grown, according to UK Soil Association (Soil Association, 2008). All samples had been sun dried in a farm field with the exception of sample number 2 which was harvested green and dried by a sunlit window over a 2 week period (Table 11, Table 12 & Figure 11).

Table 11: Sample General Information.

Sample Number	Type of straw	Genus & Species of Plant	Farming Method	Harvest Location
1	Wheat	<i>Triticum aestivum L.</i>	Conventional	North Somerset, South West England.
2	Wheat	<i>Triticum aestivum L.</i>	Organic	North Somerset, South West England.
3	Barley	<i>Hordeum vulgare L.</i>	Conventional	Essex, South East England.
4	Barley	<i>Hordeum vulgare L.</i>	Conventional	North Somerset, South West England.
5	Rice	<i>Oryza sativa L.</i>	Organic	Carmague, Southern France.
6	Rice	<i>Oryza sativa L.</i>	Conventional	Carmague, Southern France.



Figure 11: Photographs of samples before experiments.

Table 12: Qualitative Description of Samples.

Sample Number	Visual Appearance	Colour	Odour
1	Loose, broken stems, some ear included, dark patches on surface	Pale golden	Dusty
2	Stiff strong whole stems, some ear included, shiner/waxy inner layer stem	Pale golden	Fresh
3	Broken stems, shinny/waxy	Bright golden	Fresh
4	Hollow thin stems, waxy, dark dots on surface	Bright golden	Clean
5	Less waxy, some empty ears included, some dark blotches on surface	Pale golden	Fresh
6	Less waxy, some dark blotches on surface	Pale golden	Fresh

3.2.2 Calculation of moisture content

The original MC of each sample was calculated in order to know the moisture contained within each sample before experiments began (Table 13). Dry basis moisture content was calculated by weighting specifically, rather than through the use of sensors, for these have been found to be less accurate at higher moisture content (Carfrae, 2008). Dry moisture content was adopted rather than wet basis moisture content in order to make comparisons with Summers. Dry basis moisture content is the weight of water over the weight of dry material (Summers, 2003, p2).

MC was calculated according to the British Standard for drying building materials (British Standard Institution, 2000). The MC is calculated from the mass of the sample before drying and the mass of the sample after drying at an elevated temperature. MC was calculated using the following steps:

1. 10 grams of material was randomly selected from a sample of straw;
2. The sample was cut into 25 mm lengths;
3. The sample was weighed using scales with an uncertainty of no greater than 0.01 grams (see Appendix);
4. The sample was then dried in an oven at 105⁰C. The sample was considered dry once MC stopped decreasing to 0.1% of the original sample weight. This was achieved by weighing samples after 1 hour and reweighing samples at 2 hours. Samples that had been oven dried were discarded and not used in further experiments.

Table 13: Moisture Content of Samples.

Sample Number	Moisture Content (MC) % (Dry Basis)
1	9.1
2	11.8
3	8.2
4	11.5
5	11
6	11

3.2.3 Method description

1. The experiments were conducted in a small, insulated, lightless room. The room measured 800mm by 700mm and 2800mm high. The temperature within the room was 30°C (+/- 1°C). The temperature was controlled using a heater and thermostat, with separate thermometers being used to monitor room temperature. Two experiments were conducted at the same time, using separate GA 2000 gas analysers and containers (Figure 12). Each container functioned as a closed system bioreactor; maximising microorganism activity within a closed environment. The following steps were used for each experiment: Samples were randomly selected and cut into 25 mm lengths;
2. 2.1 litre plastic (HDPE) containers were washed and cleaned using a mild bleach solution, rinsed and allowed to dry at room temperature;
3. Each container was perforated in two locations; an inlet and outlet rubber tube placed through these and then sealed using Ceresit 10B High Performance Silicone. 15.55 grams of sample was added to the 2.1 litre HDPE plastic container. The amount of sample added to the container was based on a container volume to sample ratio of 0.135 litre/dry gram (Summers, 2002). All weighing was conducted using Durascale 100 scales to an accuracy of 0.00 (Appendices).
4. Water was added to the container to create 160% MC. 24.8 grams of water minus the water already in the sample was added. The water already in the sample was calculated from the MC of each sample. The sample and water were mixed together to ensure even distribution..
5. The containers were sealed using Teflon tape on the thread of the lids. A plastic bag was then placed over the entire container and sealed in order to further minimise gas exchange.
6. CO₂, CH₄, O₂, H₂S, barometric pressure, time and date were recorded using GA 2000 Landfill Gas Analysers (GA1 and GA2) (see Appendix). The temperature of the sample within the container connected to GA2 was also taken using a temperature probe.
7. Data was recorded every hour for approximately 100 hours, although this varied depending on the results of a particular sample.
8. Upon completion samples were observed for visible and odorous signs of decay.
9. Samples were then dried to determine any mass loss during the experiment.
10. A minimum of 3 repetitions of each sample was undertaken.

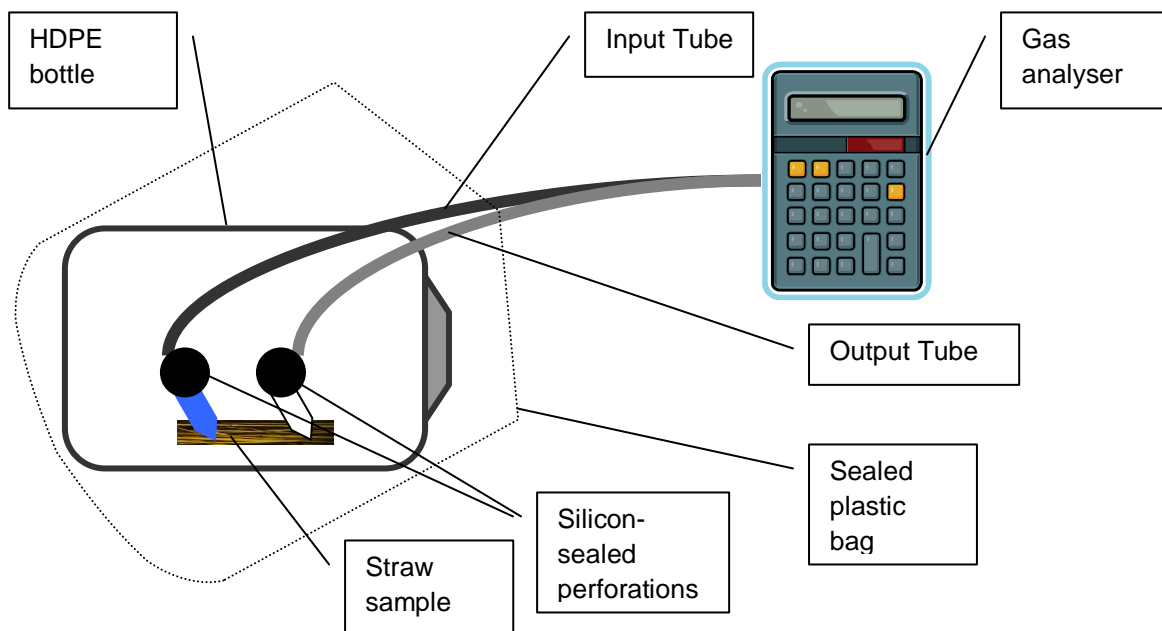


Figure 12: diagram of experiments.

In order to gauge the amount of degradation that occurred during experiments the % of CO₂ in the atmosphere was converted into kg CO₂/kg of dry straw. Conversion of % CO₂ to kg CO₂/kg dry straw was accomplished by solving for n while using the ideal gas law: $PV=nRT$ (see Appendix). CO₂ was assumed to be an ideal gas, for the purposes of this experiment.

This chapter has examined the methodology considered for this study and the method used. The next chapter describes the results obtained from the method used, followed by analysis of those results.

3.3 Summary of Chapter 3

This chapter has detailed the methodology considered with this research. The method used has been described, including details about the straw samples used. Chapter 4 describes the results found and provides analysis of those results.

4 Results and Analysis

The aims of this chapter are to present the results from experiments conducted using the method described in Chapter 3. The following information is presented in the sections below:

1. An example of the data received during experiments;
2. Visual and odorous descriptions of the samples;
3. The amount of decay that occurred in samples during experiments, quantified using three parameters: a) maximum CO₂ produced; b) the time taken for maximum CO₂ to be produced; and c) the rate at which CO₂ was produced up until the maximum amount was reached. The mean and standard deviation of these decay parameters are calculated for each sample.

Analysis of these results is then undertaken with reference to the thesis objectives, as presented in Chapter 1. Analysis includes:

- Explanation of the biological processes believed to occur during experiments;
- Application of the Mann Whitney U test (using the statistical software, Minitab) to analyse the variation between samples of the same straw type;
- Application of the one-way analysis of variation (ANOVA) statistical tool (in MS Excel), to examine the variation between straw types;
- Use of the Mann Whitney U test to analyse the difference between conventional and organically grown straw.

Variation between samples and between straw types is completed using the three parameters: maximum CO₂ production, time and rate.

4.1 Results

The atmospheric concentrations of the gases concerned in this study are 21 % O₂, 0.04 % CO₂ and very small concentrations of CO (Pidwirny, 2007). The % of gas in the atmosphere (CO₂, O₂ and CO) within the experimental container in a typical straw sample is shown for a 94 hour period as an example of a raw data trace (Figure 13). CO₂ is shown to steadily increase and O₂ steadily decreases over time. CO₂ reaches a maximum of 19.7 % at 93 hours. O₂ reaches 0 % concentration at 75 hours. CO shows small variations and then rapidly increases in % from 82 hours. An average CO₂ rate of 0.21 was calculated using the maximum CO₂ produced from the start of the experiment to the time at which max CO₂ was reached (i.e. 93 hours). The results are presented as kg CO₂/kg dry straw. CO and H₂S were also recorded in high concentrations for samples 2, 3 & 5 (see Appendix). The remainder of this thesis concerns CO₂ gas only, for there is a direct relationship between decay in straw and CO₂. Observations were also made of the physical appearance and odour of the straw at the conclusion of experiments.

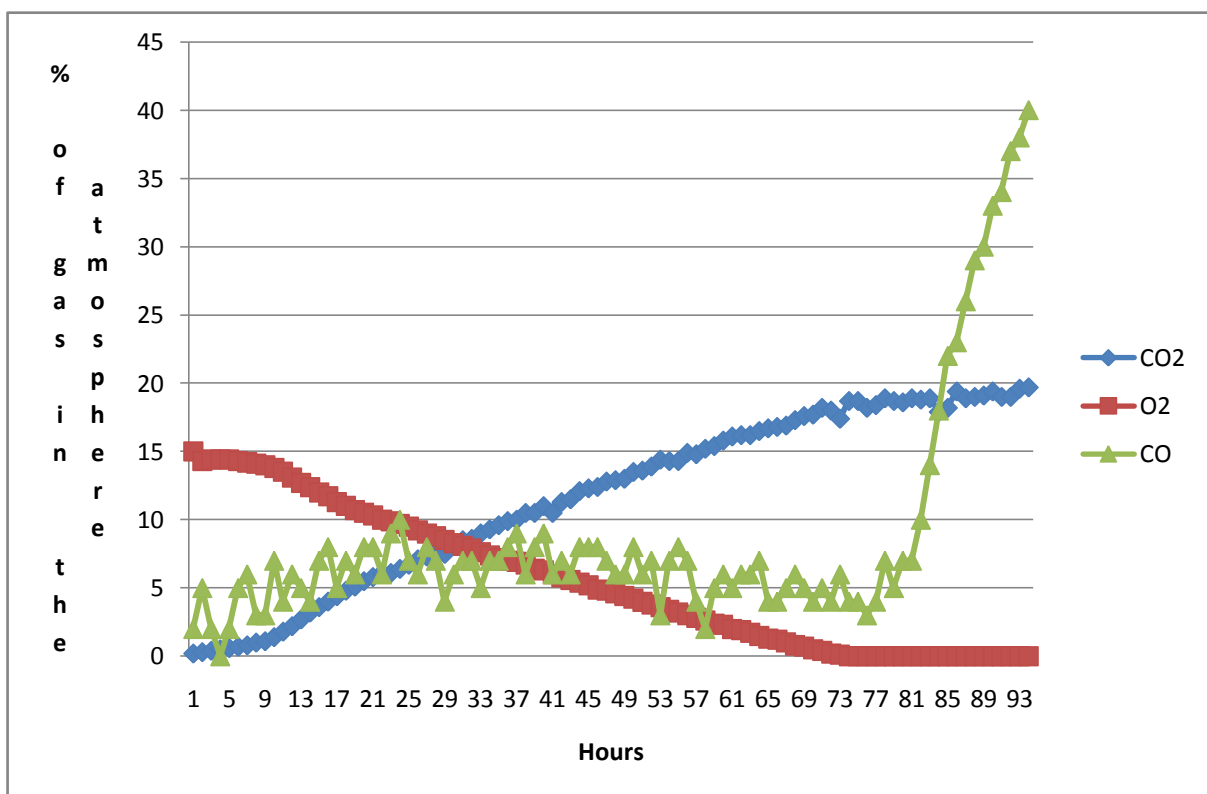


Figure 13: % of gas in atmosphere for barley (sample 3b) over 94 hours.

Experimental results are summarised in Table 14. Three runs were completed for samples 1, 2, 4 and 6. Four runs were completed for samples 3 and 5. Higher values reported for maximum CO₂ production and rate indicate greater degradation in samples; conversely, lower values for time (to max CO₂) indicate greater decay. The highest maximum kg CO₂/kg dry straw produced from wheat (sample 2b) was 0.057 kg CO₂/kg dry straw. The fastest time to reach maximum CO₂ production was from wheat (sample 2c) of 27 hours. The highest rate of CO₂ production was from wheat (sample 2c) of 1.04E-03 kg/kg*hr. The lowest maximum kg CO₂/kg dry straw produced was from barley (sample 4a) of 0.009 kg CO₂/kg dry straw. The longest time to reach maximum CO₂ production was from rice (sample 5c) of 99 hours. The lowest rate of CO₂ production was from barley (sample 4b) of 1.38E-04 kg/kg*hr.

Table 14: Summary details of all samples (highest results are indicated by ‘***’; lowest results are indicated by ‘**’).

Sample	Straw type	Run	Maximum kg CO ₂ /kg dry straw (kg/kg)	Time at which maximum CO ₂ reached (hr)	Average rate of CO ₂ production (to maximum Co ₂) (kg/kg*hr ⁻¹)
1	wheat	A	0.021	83	2.53E-04
		B	0.013	93	1.40E-04
		C	0.026	77	3.38E-04
2	wheat	A	0.021	33	6.36E-04
		B	0.057**	44	1.30E-03
		C	0.028	27**	1.04E-03**
3	barley	A	0.030	89	3.37E-04
		B	0.049	94	5.21E-04
		C	0.016	49	3.27E-04
		D	0.037	87	4.25E-04
4	barley	A	0.009*	57	1.58E-04
		B	0.008	58	1.38E-04*
		C	0.023	88	2.61E-04
5	rice	A	0.028	93	3.01E-04
		B	0.010	60	1.67E-04
		C	0.031	99*	3.13E-04
		D	0.010	46	2.17E-04
6	rice	A	0.011	31	3.55E-04
		B	0.022	91	2.42E-04
		C	0.009	44	2.05E-04

The visual appearance and odour of samples changed during the experiments (Table 15 & Figure 14). All samples were warm to touch upon opening the containers. All samples showed a white growth on surface, except rice (sample 5). Dark growth was visible on most samples, particularly around the nodules or ends of cut straw.

Table 15: Visual and odorous description of samples after experiments.

Sample Number	Visual Appearance	White growth	Dark growth	Odour
1		Dots, clumps, fine fibres	None visible	Mouldy
2	Dark brown liquid	Clumps of fine fibrous growth centred over grain on head of plant	Broadly over outer surface	Mouldy
3	Looks bright & shinny	Dots	None visible	rotten egg, sulphurous
4	Looks bright & shiny	Fibres, dots, dots at nodules	None visible	rotten egg
5	Light brown liquid	None visible	Blotches on surface, Dark at ends of cut sample, Dark along inner tube, while lighter on outer tube, Dark around nodules	sulphurous
6	Dark brown liquid	At nodules	Broad brown patches over outer surface, Inner core dark, while outer shell light coloured	Grassy, mouldy



Figure 14: Photographs of samples once experiments were complete (white growth particularly apparent on sample 2 and dark growth on samples 5 & 6.

4.1.1 Wheat

Wheat samples include samples 1 and 2 (Table 16, Table 17, Table 18 & Figure 15). Sample 2b produced the maximum kg CO₂/kg dry straw at 0.057 kg/kg. Sample 2 had the highest maximum mean at 0.04 kg CO₂/kg dry straw and the highest stand deviation at 1.91E-02 kg CO₂/kg dry straw. The lowest maximum kg CO₂/kg dry straw was produced by sample 1b at 0.013 kg CO₂/kg dry straw. Sample 1 had the lowest maximum mean at 0.02 kg CO₂/kg dry straw and the lowest stand deviation at 6.56E-03 kg CO₂/kg dry straw (Table 16).

Table 16: Wheat summary details, showing maximum CO₂ production (kg CO₂/kg dry straw)

Sample	Run	Maximum CO ₂	Mean of Maximum CO ₂	Standard Deviation of the mean of the Maximum CO ₂
1	A	0.021	0.02	6.56E-03
	B	0.013		
	C	0.02026		
2	A	0.021	0.04	1.91E-02
	B	0.057		
	C	0.028		

The longest time (93 hours) to reach maximum kg CO₂/kg dry straw was reported by sample 1b (Table 17). The shortest time (27 hours) to reach maximum was reported by sample 2c. Mean maximum kg CO₂/kg dry straw was reached by sample 1 in 84 hours and by sample 2 in 35 hours. Sample 2 had the highest standard deviation of 8.62 hours.

Table 17: Wheat summary details, showing time taken to reach maximum production (kg CO₂/kg dry straw).

Sample	Run	Time at which maximum CO ₂ reached	Mean Time (hr)	Standard deviation of mean time
1	A	83	84.33	8.08
	B	93		
	C	77		
2	A	33	34.66	8.62
	B	44		
	C	27		

The highest rate of CO₂ production was recorded by sample 2b and the lowest by sample 1b (Table 18). Sample 2 recorded the highest mean rate at 9.92E-04 kg/kg*hr and the highest stand deviation at 3.35E-04 kg/kg*hr. Sample 1 recorded the lowest mean rate at 2.44E-04 kg/kg*hr and the lowest stand deviation at 9.93E-05 kg/kg*hr.

Table 18: Wheat summary details, showing the average rate of CO₂ production (kg/kg*hr-1).

Sample	Run	Average rate of CO ₂ production (to maximum Co ₂)	Mean rate	Standard deviation of the mean rate
1	A	2.53E-04	2.44E-04	9.934E-05
	B	1.40E-04		
	C	3.38E-04		
2	A	6.36E-04	9.92E-04	3.35E-04
	B	1.30E-03		
	C	1.04E-03		

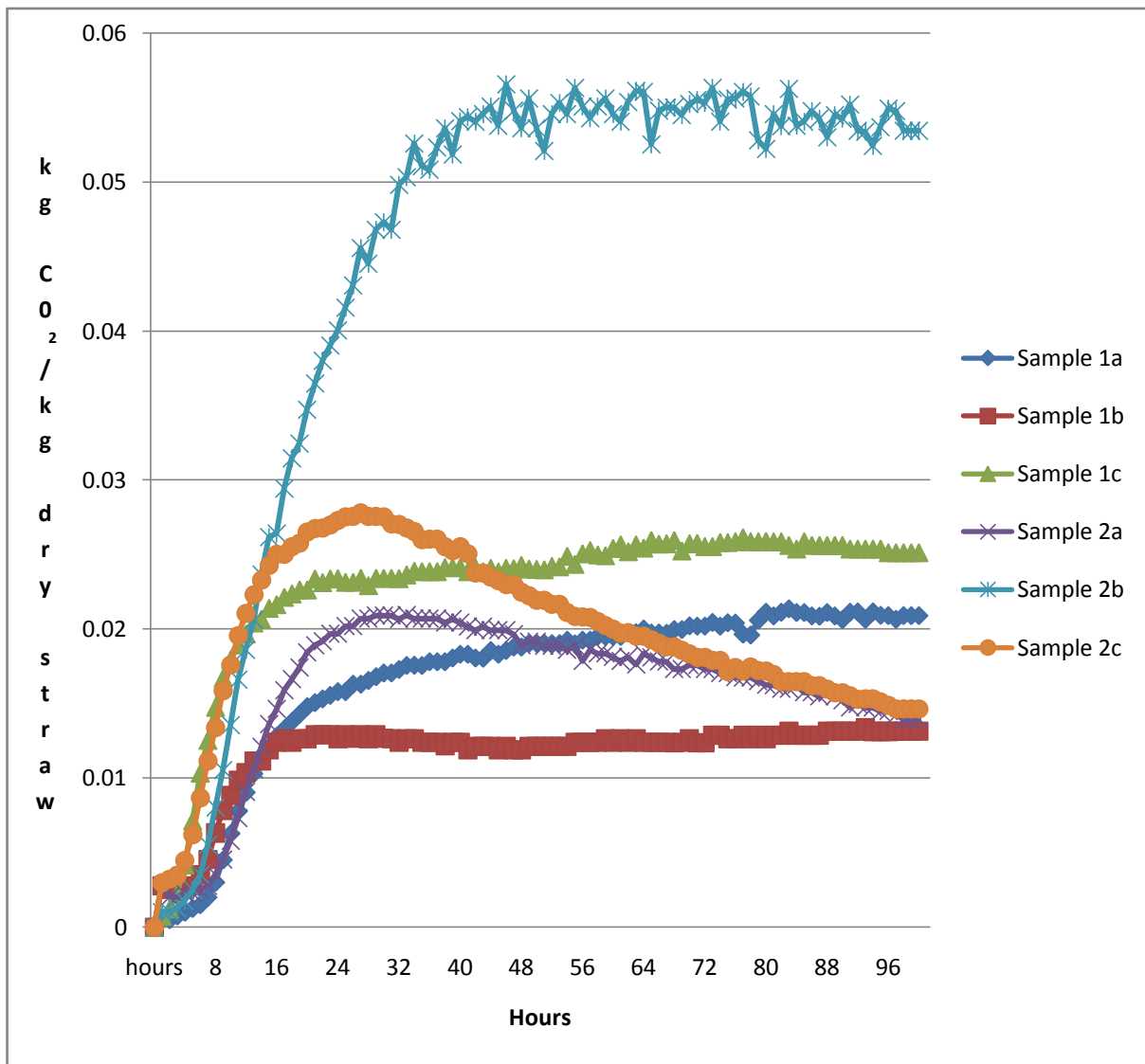


Figure 15: Wheat details, showing kg CO₂/kg dry straw produced over 100 hours.

4.1.2 Barley

Barley samples include sample 3 and 4 (Table 19, Table 20, Table 21 & Figure 16). Sample 3b produced the maximum production at 0.049 kg CO₂/kg dry straw (Table 19). Sample 3 had the highest maximum mean at 0.033 kg CO₂/kg dry straw and the highest stand deviation at 1.38E-02 kg CO₂/kg dry straw. Sample 4b produced the lowest maximum production at 0.008 kg CO₂/kg dry straw. Sample 4 had the lowest maximum mean at 0.01 kg CO₂/kg dry straw and the lowest standard deviation at 8.39E-03 kg CO₂/kg dry straw.

Table 19: Barley summary details, showing maximum CO₂ production (kg CO₂/kg dry straw)

Sample	Run	Maximum CO ₂	Mean of Maximum CO ₂	Standard deviation of the mean of the Maximum CO ₂
3	A	0.030	0.033	1.38E-02
	B	0.049		
	C	0.016		
	D	0.037		
4	A	0.009	0.01	8.39E-03
	B	0.008		
	C	0.023		

Sample 3b took the longest time to reach maximum production at 94 hours and sample 3c took the shortest time to reach maximum production at 49 hours (Table 20). Mean maximum was reached by sample 3 at 79.75 hours and at 67.67 hours for sample 4. Sample 3 had the highest stand deviation at 20.71 hours.

Table 20: Barley summary details, showing time taken to reach maximum production (kg CO₂/kg dry straw).

Sample	Run	Time at which maximum CO ₂ reached	Mean Time (hr)	Standard deviation of mean time
3	A	89	79.75	20.71
	B	94		
	C	49		
	D	87		
4	A	57	67.67	17.62
	B	58		
	C	88		

The highest rate of CO₂ production was recorded by sample 3b and the lowest was sample 4b (Table 21). Sample 3 recorded the highest mean rate at 4.03E-04 kg/kg*hr and the

highest stand deviation at 9.04E-05 kg/kg*hr. Sample 4 recorded the lowest mean rate at 1.86E-04 kg/kg*hr and the lowest stand deviation at 6.60E-05 kg/kg*hr.

Table 21: Barley summary details, showing the average rate of CO₂ production (kg/kg*hr-1).

Sample	Run	Average rate of CO ₂ production (to maximum Co ₂)	Mean rate	Standard deviation of the mean rate
3	A	3.37E-04	4.03E-04	9.04E-05
	B	5.21E-04		
	C	3.27E-04		
	D	4.25E-04		
4	A	1.58E-04	1.86E-04	6.60E-05
	B	1.38E-04		
	C	2.61E-04		

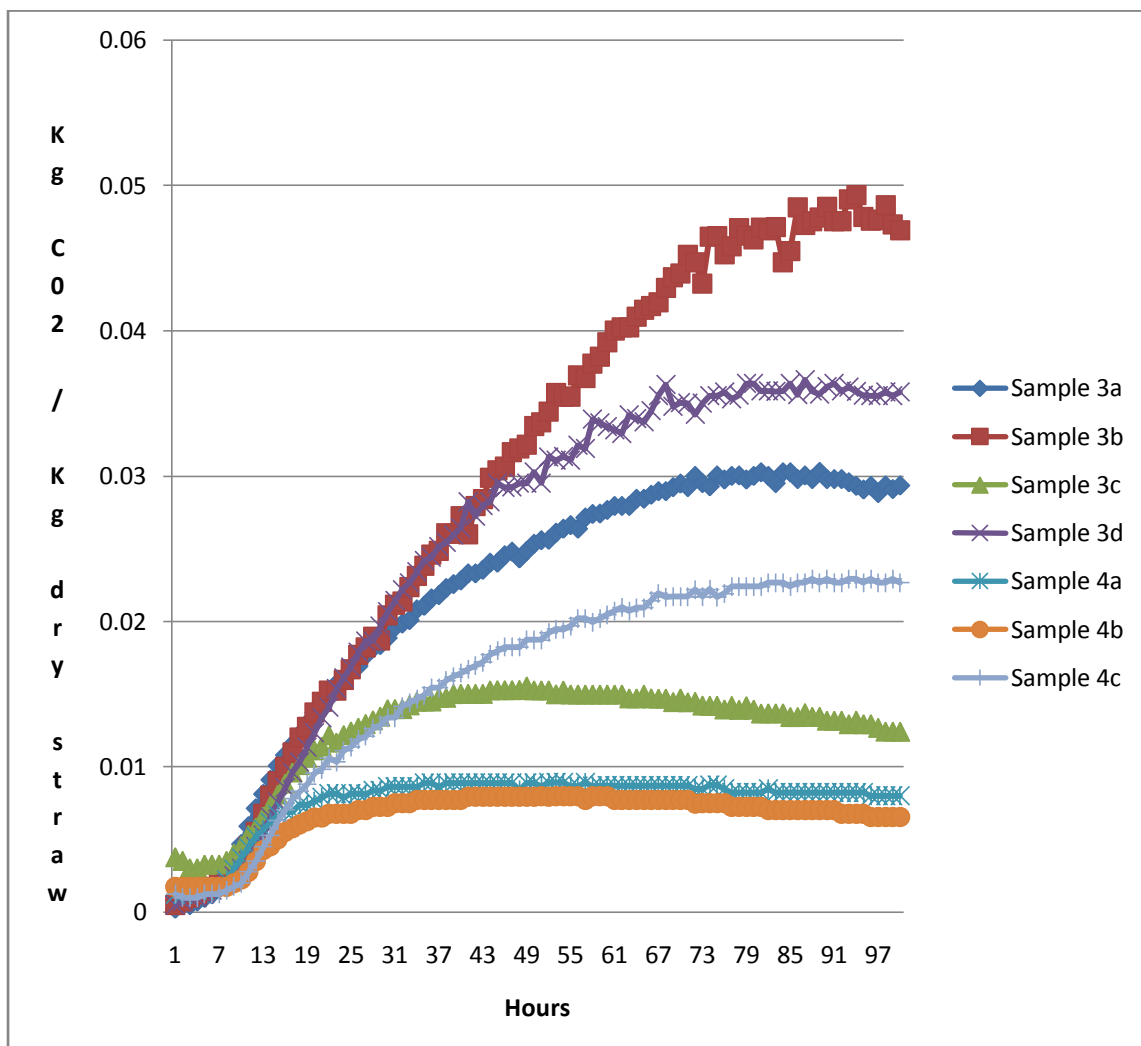


Figure 16: Barley details, showing kg CO₂/kg dry straw produced over 100 hours.

4.1.3 Rice

Rice samples included samples 5 and 6 (Table 22, Table 23, Table 24 & Figure 17). Sample 5c recorded the maximum production at 0.031 kg CO₂/kg dry straw (Table 22). Sample 5 had the highest maximum mean at 0.020 kg CO₂/kg dry straw and the highest stand deviation at 0.011 kg CO₂/kg dry straw. The lowest maximum production was recorded by samples 5b & 5d at 0.01 kg CO₂/kg dry straw. Sample 6 had the lowest maximum mean at 0.014 kg CO₂/kg dry straw and the lowest stand deviation at 0.007 kg CO₂/kg dry straw.

Table 22: Rice summary details, showing maximum CO₂ production (kg CO₂/kg dry straw)

Sample	Run	Maximum	Mean of Maximum	Standard deviation of the mean of the Maximum
5	A	0.028	0.020	1.13E-02
	B	0.01		
	C	0.031		
	D	0.01		
6	A	0.011	0.014	7.00E-03
	B	0.022		
	C	0.009		

Sample 5c took the longest time to reach maximum production (99 hours) and sample 6a took the shortest time to reach maximum production (31 hours) (Table 23). Mean maximum production of kg CO₂/kg dry straw was reached by sample 5 (74.5 hours) and by sample 6 (55.33 hours). Sample 6 had the highest stand deviation (31.57 hours).

Table 23: Rice summary details, showing time taken to reach maximum production (kg CO₂/kg dry straw).

Sample	Run	Time at which maximum CO ₂ reached	Mean Time (hr)	Standard deviation of mean time
5	A	93	74.5	25.59
	B	60		
	C	99		
	D	46		
6	A	31	55.33	31.57
	B	91		
	C	44		

The highest rate of CO₂ production was 3.55E-04 kg/kg*hr by sample 6a and the lowest was 1.67E-04 by sample 5b (Table 24). Sample 6 recorded the highest mean rate at 2.67E-04 kg/kg*hr and the highest stand deviation at 7.8143E-05 kg/kg*hr. Sample 5 recorded the lowest mean rate at 2.50E-04 kg/kg*hr and the lowest stand deviation at 6.96348E-05 kg/kg*hr.

Table 24: Rice summary details, showing the average rate of CO₂ production (kg/kg*hr-1).

Sample	Run	Average rate of CO ₂ production (to maximum Co ₂)	Mean rate	Standard deviation of the mean rate
5	A	3.01E-04	2.50E-04	6.96E-05
	B	1.67E-04		
	C	3.13E-04		
	D	2.17E-04		
6	A	3.55E-04	2.67E-04	7.81E-05
	B	2.42E-04		
	C	2.05E-04		

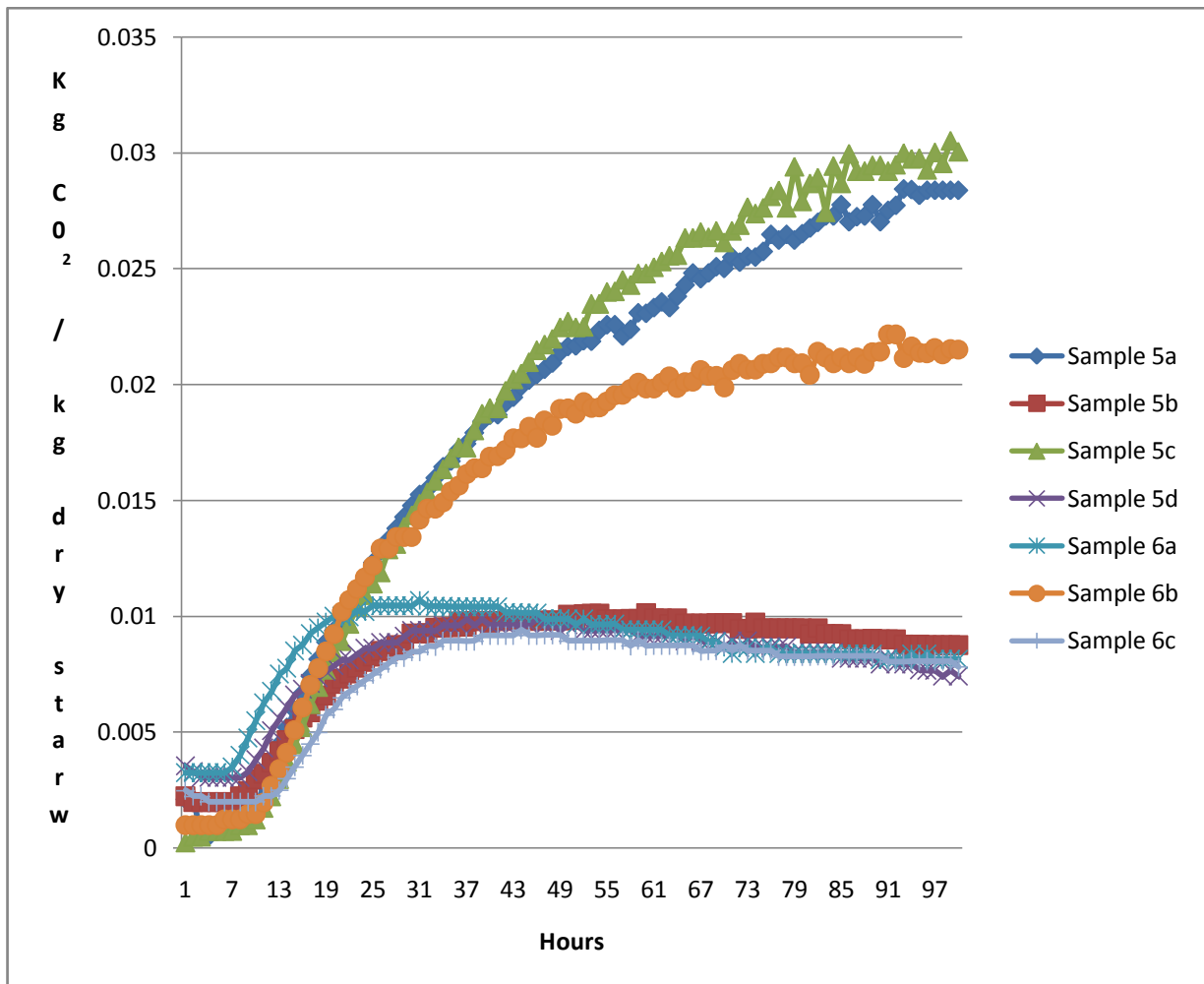


Figure 17: Rice details, showing kg CO₂/kg dry straw produced over 100 hours.

4.1.4 Comparison between different straw types

Wheat straw is represented by samples 1 & 2. Barley straw is represented by samples 3 & 4. Rice straw is represented by samples 5 & 6. The mean and standard deviation of maximum CO₂ production, time and rate have been calculated (Table 25, Figure 18, Figure 19 & Figure 20). The lowest mean maximum CO₂ production was recorded by rice (0.017 kg CO₂/kg dry straw) and the lowest standard deviation maximum was recorded by rice (0.010 kg CO₂/kg dry straw). The highest mean maximum was recorded by wheat (0.028 kg CO₂/kg dry straw) and the highest standard deviation maximum was recorded by wheat (0.0153 kg CO₂/kg dry straw). The lowest time to maximum was recorded by wheat (60 hours). The highest standard deviation to maximum was recorded by wheat (28 hours). The highest time to maximum was recorded by barley (74.57 hours). The lowest standard deviation to mean maximum was recorded by barley (18.96 hours). The fastest rate of production was recorded by wheat (6.18E-04 kg/kg*hr). The largest standard deviation of mean rate was recorded by wheat (4.66E-04 kg/kg*hr). The slowest rate of production was recorded by rice (2.57E-04 kg/kg*hr). The smallest standard deviation of mean rate was recorded by rice (6.75E-05 kg/kg*hr).

Table 25: Summary of straw samples: mean and standard deviation of maximum production, time and rate.

	Maximum (kg CO ₂ /kg dry straw)	+/-	Time (hr)	+/-	Rate of CO ₂ production (kg/kg*hr ⁻¹)	+/-
Wheat	0.028	0.0153	59.50	28.21	6.18E-04	4.66E-04
Barley	0.025	0.0151	74.57	18.96	3.10E-04	1.38E-04
Rice	0.017	0.010	66.29	27.65	2.57E-04	6.75E-05

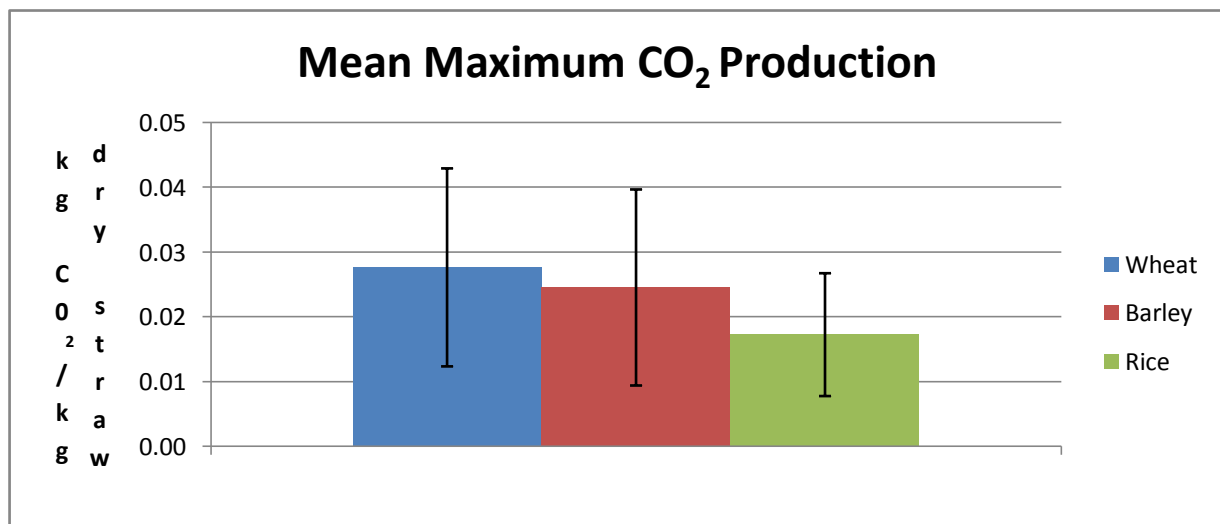


Figure 18: Mean maximum CO₂ production and standard deviation for straw types.

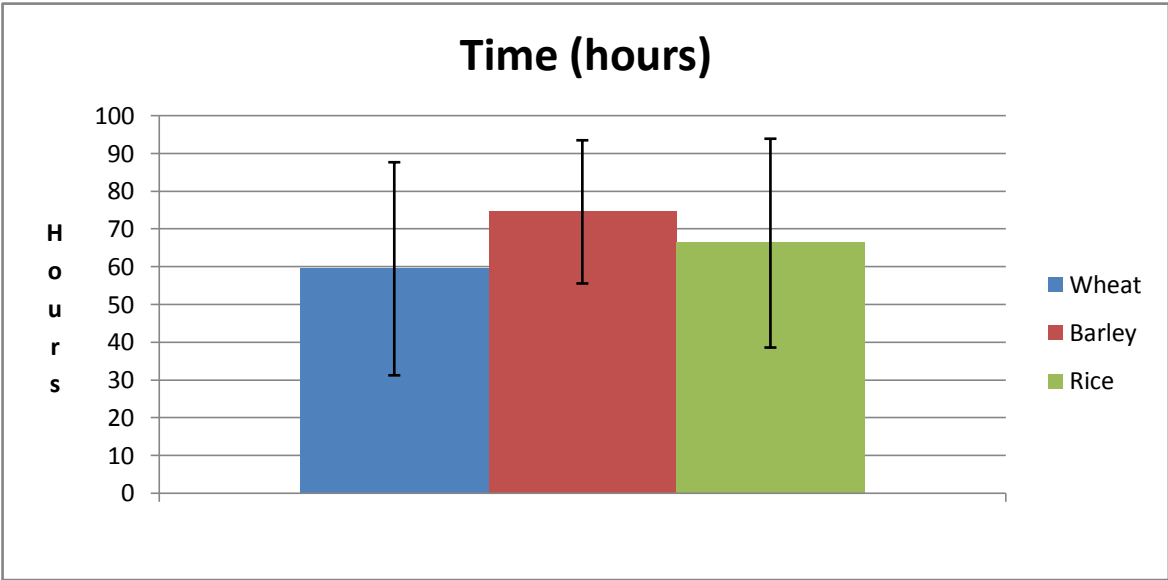


Figure 19: Mean time and standard deviation for straw samples.

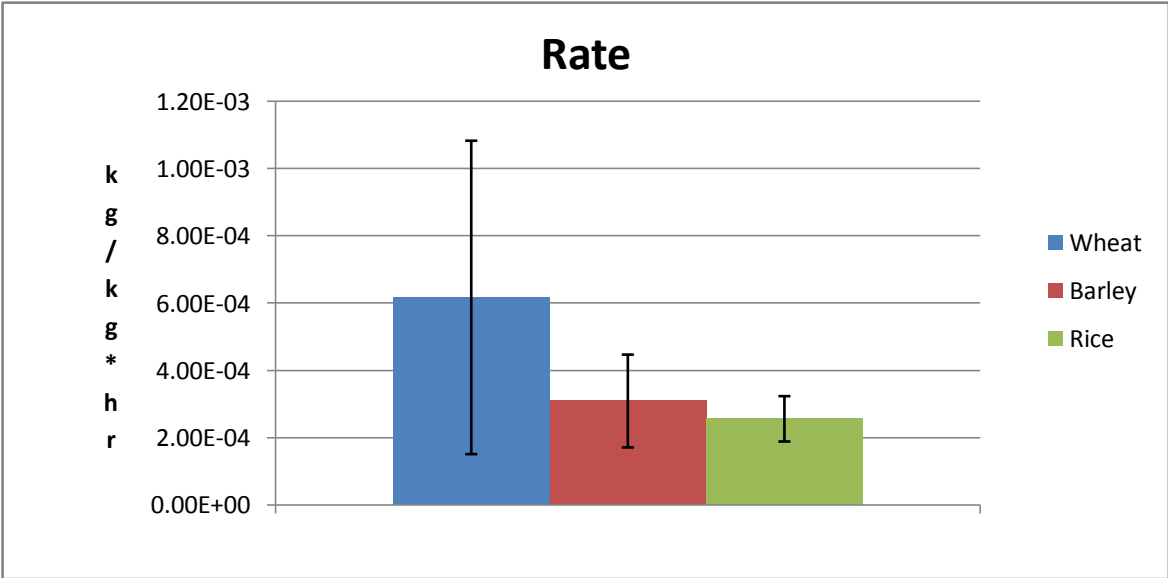


Figure 20: Mean rate and standard deviation of CO₂ production for straw samples.

4.2 Analysis

4.2.1 Explanation of Biological Processes Occurring During Experiments

The large deviation of gas concentrations away from atmospheric gas concentrations seen in Figure 13 is most likely the result of multiple populations of microorganisms feeding on the straw samples and emitting CO₂ gas as a product of their biological processes. Straw (regardless of type) typically hosts a variety of microorganisms when harvested (Summers, 2003, p1). Microorganisms remain in a stage similar to hibernation until the right environmental conditions are encountered to stimulate activity (Oliver, 2005, p93). Once these environmental parameters have been met, then microorganisms initiate a sequence of distinct lifecycle phases (Sedlbaur, 2001, p36). The four main requirements for microorganism activity were sufficient nutrients, oxygen, optimum temperature, and moisture (see Section 2.5). The atmosphere in the containers is closed to the outside atmosphere, therefore any change in gas concentrations are the result of microorganisms decaying the straw. It should be noted that a small amount of gas exchange occurred between inside the container and outside from leakage of seals and the semi permeable plastic container used (see Chapter 3). Both fungi and bacteria are likely to have been active on the straw samples, although only analysis in a laboratory would prove their existence.

Three distinct phases were identified from the results (Figure 13), as follows:

Phase 1: 0-10 hours. As can be seen from Figure 13, within a few hours of starting the experiments CO₂ and O₂ levels begin to steadily change. It is most likely that microbes are decaying the straw; with O₂ being consumed through respiration and CO₂ is being produced. Initially, microbes need to activate metabolic processes and produce enzymes; therefore activity is gradual, as seen by the slow change in O₂ and CO₂ gases (Panikov, 1995, p7). This initial stage can take hours or days, depending on environmental conditions (Fog Nielsen, 2002). The enzymes break down plant C (cellulose & hemicelluloses) in straw, providing microbes with energy (Wihan, 2007). Glucose is released when the cellulose in the plant material is broken down and fed upon by microbes (Daglish, 1994, p9). Some of the energy is used by the microorganisms for reproduction and growth; the rest is given off as heat (Jenkins, 2005, p42). This heat was noted by the warmth felt upon opening the containers at the completion of each experiment. Heat generation during these experiments was limited because the laboratory temperature had been controlled; however, some heat gain within the sample container was recorded (see Appendix).

Phase 2: 10-70 hours. This phase is signified by a rapid increase in CO₂ and a rapid decrease in O₂. It is likely that microbes have now activated their metabolic processes and increased dispersal of enzymes to decay straw. Microbes that prefer an aerobic environment are most likely to be active during this phase. This is the period during which the most rapid rate of degradation of straw occurs. Activity during this period is likely to be primarily fungi, such as the white fibrous growth seen in Figure 2, Sample 1.

Phase 3: 70-93 hours. This phase is signified by O₂ reaching very small amounts and the rapid production of CO. The decrease in microbe activity is possibly the result of changed environmental conditions. With the decrease in O₂, the atmosphere has changed from aerobic to anaerobic. This is a limiting factor to aerobic microbes and likely to be the reason for the slowed rate of CO₂ production. Other changes to the environmental conditions of the microorganisms could include a lack of nutrients and/or a build up of waste products (Button, 1985, p270). And at the same time, it is likely that anaerobic microbes will be increasing their activity and producing CO. CO is produced by microbes when they rot plant matter

(Manahan, 2005, p301), forming in preference to CO₂ where O₂ is limited. One explanation for the small and varying percent of CO for the first 70 hours is that until the O₂ levels decline, the microorganisms that prefer low O₂ environments will have had limited activity.

Anaerobic microbes also produce hydrogen as a waste product of decay activity (ATSDR, 2001, p2). It is likely that the rotten egg smell observed when opening sample containers at the completion of many of the experiments (Table 15) signifies the production of hydrogen sulphide. Hydrogen sulphide is a by-product of bacteria during the biodegradation of plant material, such as straw (ATSDR, 2001). The dark liquid observed in some of the containers likely to be a liquid generated by anaerobic bacteria (Leggitt, 1996) (Table 15). It is possible that aerobic microbes released spores during this period, so as to ensure a future generation of aerobic microbes.

Microbe populations oscillate with the environmental conditions. During this study, it is possible that thousands of different fungi and bacteria were actively decaying straw. There is also likely to be significant overlap of different microbes being active at the same time. Each different fungi or bacteria would have been active under their own individual optimum environmental conditions. These conditions maybe a particular temperature, moisture content, gas concentration or C:N ratio. For example, different bacteria prefer particular temperatures for optimum growth (Table 26) (Jenkins, 2005). Typically, as degradation begins, the temperature will rise, therefore resulting in bacterial activity, first from psychrophiles, then mesophilic and finally thermophiles, if the temperature gets that high.

Table 26: Bacteria optimum temperature requirements (Jenkins, 2005).

Bacteria	Preferred Temperature (°C)
Psychrophiles	-10 to 15
Mesophilic	20 to 45
Thermophiles	45 to 100

Another study found a particular sequence of microorganism activity depending on the moisture content of straw (Fog Nielson, 2002). As moisture increased in straw, fungi colonised first. The fungi that colonised first (at lower moisture content) were found to be *eurotium* and *aspergillus*. In fact, *aspergillus*, has been found to be a principal fungi species on growing and recently harvested wheat straw. As moisture content increased, the fungi, *penicillium*, *cladosporium*, *alternaria* and *chaetonium* colonised. Bacteria required higher moisture content than fungi and were last to colonise (Fog Nielson, 2002, p5). Another study found that different fungi prefer different C:N ratio's (Lindahl *et al*, 2006). As a result, the first fungi colonisers to begin decay would be ones that prefer a high C:N ratio. Then fungi would be followed by fungi that prefer a lower C:N ratio.

4.2.2 Comparison with Summers *et al*, 2003.

Comparison between this research and Summers *et al*, 2003 are made in order to support the results found in this study. As with this study, Summers *et al*, 2003 used CO₂ production as a measure of degradation in straw. Likewise, the method used to run experiments was similar to the method used in this study. For these reasons, the results of Summers *et al*/ 2003 and this research are worth comparing (Figure 21). The straw used in the Summers study was conventionally grown rice straw. Summers *et al*/2003 used similar environmental conditions, except the temperature were 20⁰ C rather than 30⁰C. In this one example from Summers *et al*, 2003 as seen in Figure 9, results on average indicate higher decay rates than those found in the present study. If this one sample of Summers is representative of Summers results generally, then this suggest the CO₂ production rates found in the present study are similar to Summers.

Why the results from this study differ from Summers is likely to be the result of many factors. The straw used in Summers study was grown in the USA compared to the UK. As a result, the environmental conditions will have been different, which affects the amount of straw decay. Such as, the weather, the amounts of nutrients, how dry the straw was and the method of storage of the straw, to name just a few. Summers may have had higher quantities of microbes on the straw and this would have resulted in higher degradation rates. Or that the types of microbes present on Summers straw where particularly suited to the environmental conditions generated during his experiments and this resulted in higher decay rates.

Summers results show a continued increase in CO₂ production after the results from this study have reached a plateau or are declining (Figure 21). This could be a variety of reasons for this. The particular microbes in my study that produced CO₂ may have ended their lifecycle and therefore stopped or slowed in their CO₂ production. Where as in Summers study, a different combination of microbes, may be able to produce CO₂ to higher quantities. Also, microbes maybe still active in my study, however, they may be producing CO as a result of decay, rather than CO₂. It is difficult to make comparisons between these 2 studies with so many different confounding variables.

The results found in the current study are consistent with Summers *et al*, 2003, which was a similarly designed study. This suggests that the CO₂ production rates found in both studies are representative of the CO₂ produced while straw is decayed by microorganisms.

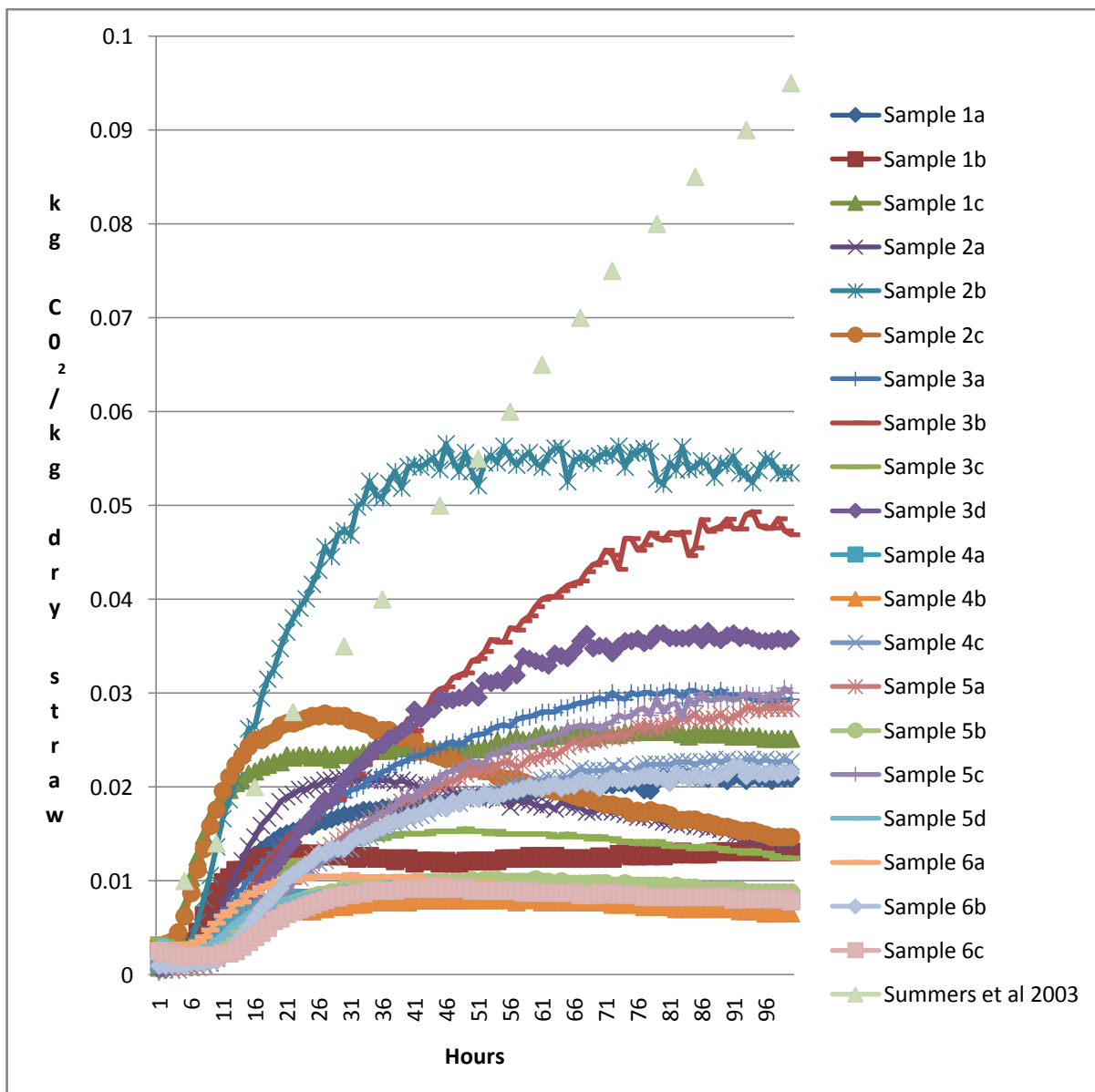


Figure 21: Results comparison between this research and Summers *et al*, 2003.

4.2.3 Sample Mean and Standard Deviation within Straw Type

Analytical comparisons are now made of the different samples of straw within the same type of straw. For wheat straw, sample 1 is compared to sample 2; for barley straw, sample 3 is compared to sample 4 and for rice straw, sample 5 is compared to sample 6.

Sample 2 has a higher mean and standard deviation of maximum CO₂ production and rate compared to sample 1 as a result of the much higher maximum and rate of sample 2b. Further experiments would be needed to gauge whether or not sample 2b is an outlier. Sample 3 has a higher mean and standard deviation of maximum CO₂ production, time and rate compared to sample 4. This suggests that sample 3 & sample 4 have different decay characteristics, even though they are the same type of straw. The differences between the mean and standard deviation between samples 5 & 6 are less notable than the differences between wheat samples and particularly between barley samples.

Variation between samples of the same straw is examined in the following section using sample medians and the Mann Whitney U Test.

4.2.4 Wheat

The two sample Mann Whitney U test was used to make inferences about the difference between samples 1 and sample 2 medians. The null hypothesis is that sample 1 is not significantly different than sample 2. The alternative hypothesis is that sample 1 is significantly different than sample 2. In Minitab, the estimated medians for the two samples were calculated, together with an approximate 95% confidence interval for the difference between the medians and resultant p value (Table 27). In reference to the p values for all three decay parameters, there is little evidence of a significance difference between the medians. Maximum CO₂ production variation is similar between samples 1 & 2. There is some evidence of variation in time and rate for samples 1 & 2. No significant difference was found between sample 1 & 2.

Table 27: Results of Mann Whitney U Test on wheat samples (samples 1 & 2).

Decay parameters	Sample	Median	P Value
Maximum CO ₂ Production (kg CO ₂ /kg dry straw)	1	0.021	0.2683
	2	0.028	
Time (hr)	1	83	0.0809
	2	33	
Rate (kg/kg*hr)	1	0.00025	0.0809
	2	0.00104	

4.2.5 Barley

The two sample Mann Whitney U test was used to make inferences about the difference between sample 3 and sample 4's medians. The null hypothesis is that sample 3 is not significantly different than sample 4. The alternative hypothesis is that sample 3 is significantly different than sample 4. In Minitab, the estimated medians for the two samples were calculated, together with an approximate 95% confidence interval for the difference between the medians and resultant p value (Table 28). In reference to the p values for all three decay parameters, there is little evidence of a significance difference between the medians. There is moderate evidence for variation in maximum CO₂ production between sample 3 & 4. There is little evidence of variation in time between samples 3 & 4. The rate of CO₂ production is almost significantly different between samples 3 & 4. No significant difference was found between samples 3 & 4.

Table 28: Results of Mann Whitney U Test on barley samples (samples 3 & 4).

	Sample	Median	P Value
Maximum CO ₂ Production (kg CO ₂ /kg dry straw)	3	0.0335	0.1116
	4	0.0090	
Time(hr)	3	88	0.5959
	4	58	
Rate (kg/kg*hr)	3	0.00038	0.0518
	4	0.00016	

4.2.6 Rice

The two sample Mann Whitney U test was used to make inferences about the difference between medians for sample 5 and sample 6 (Table 29). The null hypothesis is that sample 5 is not significantly different than sample 6. The alternative hypothesis is that sample 5 is significantly different than sample 6. In Minitab, the estimated medians for the two samples were calculated, together with an approximate 95% confidence interval for the difference between the medians. In reference to the p values for all three decay parameters, there is little evidence of a significance difference between the medians. Maximum CO₂ production, time and the rate of CO₂ production have similar variation between samples 5 & 6. No significant difference was found between sample 5 & 6.

Table 29: Results of Mann Whitney U Test on rice samples (samples 5 & 6).

	Sample	Median	P Value
Maximum CO ₂ Production (kg CO ₂ /kg dry straw)	5	0.0190	0.5926
	6	0.0110	
Time (hr)	5	76.5	0.2159
	6	44	
Rate (kg/kg*hr)	5	0.00026	0.8597
	6	0.00024	

In conclusion, the variation of median within samples of the same straw has not been found to be significantly different. However, based on p value results, some notable variation exists. Wheat samples have moderate variation in time and rate. Barley samples have moderate variation in maximum CO₂ production. Barley samples almost have significantly different variation for rate. Rice samples have the least amount of variation.

The analysis from the Mann Whitney U Test does not prove that there is significant difference of median between samples of the same type of straw. The accuracy of this analysis is questionable. The small number of samples combined with the high degree of variability found within samples suggests that in order to establish the variation within straw type a higher numbers of samples are required.

The next section compares the results of organic and conventionally grown straw samples.

4.2.7 Comparison between organically and conventionally grown straw

Both organic and conventionally grown straw was included in this study (see Chapter 2). A Mann Whitney U test in Minitab was completed in order to compare the decay parameters of organic versus conventionally grown straw (Table 30). A confidence interval of 95 % was chosen; therefore p values less than .05 would be significant. In reference to the p values for all three decay parameters, there is little evidence of a significance difference between the medians of organic straw versus conventionally grown straw. Organic straw may have more microorganisms on its surface due to the lack of fungicides used; however one study found that organic straw was less decayed than conventionally grown straw. This study hypothesised that this was because the organic straw had a greater silica/waxy build up on the surface of the straw and that this repelled water (Kaboneka *et al*, 2002, p152). N fertiliser applied to conventionally grown straw may supply better food source for some microbes and therefore result in higher degradation in conventionally grown straw. However, this study was unable to obtain the N concentrations present on the straw, therefore any influence on decay from N concentrations is inconclusive.

Table 30: Results of a Mann Whitney U Test on organic and conventionally grown straw.

	Sample	Growing Method	Median	P Value
Maximum CO ₂ Production (kg CO ₂ /kg dry straw)	2 & 5	Organic	0.028	0.4047
	1, 3, 4 & 6	Conventional	0.021	
Time (hr)	2 & 5	Organic	46	0.3830
	1, 3, 4 & 6	Conventional	83	
Rate (kg/kg*hr)	2 & 5	Organic	0.00031	0.2673
	1, 3, 4 & 6	Conventional	0.00026	

4.2.8 Comparison between different Straws

In order to make comparisons between different straws, the 6 samples used in this study were combined to represent the 3 types of straw being compared. However, the samples of the same straw may in fact be significantly different from each other. Therefore, by combining samples to represent one straw type may mean the straw type is not being statistically represented. Having said that, samples have not been proved to be significantly different; therefore they are being combined here, in order to attempt to compare decay between different straw types.

Wheat straw has the highest mean maximum CO₂ production, rate and then lowest time to reach that maximum (Table 25). This suggests that wheat straw will decay at a faster rate and reach a higher maximum CO₂ production level more quickly than barley or rice. Summers *et al* 2003 found that wheat had an earlier rate of degradation than rice, although no details are known of the maximum CO₂ production or time. Barley straw results show a mean and standard deviation that are indistinctive in comparison with rice and wheat.

Rice straw has the lowest mean maximum CO₂ production and rate and an average time to maximum CO₂ production (Table 25). This suggests that rice straw will decay at a slower rate and will not reach as high a maximum CO₂ production as wheat and barley straw. It has been suggested that rice straw has a high resistance to degradation because of the high silica content (see Section 2.1.3) (ref required). Silica is highly resistant to decay and located on the outside of the stem of the straw, where it acts as a protective boundary

between the microorganisms and the more easily digestible inner stem. Silica is a hydrophobic material, and as such water naturally beads on the surface rather than soaking into the straw (Straube, 1998, p4). Sample 5 of rice shows where microorganisms have ignored the outer stem and began to decay the inner stem (Figure 14,) suggesting that the outer stem is not as digestible. This priority degradation by microorganisms of the inner stem was not observed for wheat or barley straw.

Degradation has focused around the nodules or cut ends of straw (Figure 14), this suggests that less decay would occur if there were less nodules or cut ends. Rice straw and some older varieties of wheat straw, such as Maris Widgeon are substantially longer than other straws. Longer stems equals less nodules and fewer openings for microorganisms to decay (Wihan, 2007). The older longer varieties of wheat are used for thatching buildings in the UK and are chosen for their ability to resist decay better than other straws (Wakley, 2008; Shallow, 2008).

The standard deviation of the means for maximum CO₂ production, time and rate of wheat, barley and rice overlap significantly (Figure 18, Figure 19 & Figure 20). This overlap highlights the large variance within each straw type, thereby making it difficult to make conclusive comparisons between straw types.

The variation in decay between different straws is now analysed below using one way ANOVA. The variances between wheat, barley and rice straw are compared using the independent variable of decay. The decay parameters used are maximum CO₂ production, time and rate (Table 31). A confidence interval of 95 % was chosen; therefore p values less than .05 would be significant. Both maximum CO₂ production and time recorded large p values and therefore are not significantly different from each other. Rate recorded a p value only just above .05; therefore while not significant in this test, some notable variation exists. The variability in rate can be attributed to sample 2, which had an unusually fast rate of decay.

Table 31: Straw Summary Table, showing ANOVA p values and decay parameters.

Decay Parameters	P Value
Maximum CO ₂ Production (kg CO ₂ /kg dry straw)	0.375284
Time (hr)	0.566338
Rate (kg/kg*hr)	0.060315

The outlier, sample 2b, recorded substantially higher maximum CO₂ production than the other samples. As a result, additional ANOVA analysis was completed after removing 2b from the data to see if sample 2b was significantly changing the results. However, no significant change was found.

The results of this ANOVA analysis suggest that there is no significant difference in decay between wheat, barley and rice. However, due to the small sample size and the resultant large variance in results it is difficult to conclusively say there is no significant difference in decay between straw samples. The rate of decay was almost significantly different between straw types; however, this was caused by sample 2, which recorded a much higher rate of decay than other straw types, including the other wheat sample (Table 18).

SUMMARY OF ANALYSIS

COMPARISON BETWEEN SAMPLES OF THE SAME STRAW TYPE

According to the mean and standard deviation analysis:

1. Decay varies between different straws of the same straw type.

According to the sample medians and the Mann Whitney U Test analysis:

2. There is no significant difference between samples of the same straw type.

Whether or not samples of the same straw are significantly different from each other is questionable based purely on the experiments undertaken in this study. The large variability found within the small sample size tested suggests the need for the testing of more samples. By increasing sample size the statistical significance of the results would be stronger.

COMPARISONS BETWEEN ORGANIC AND CONVENTIONAL STRAW

There is little evidence of a significant difference between organic and conventionally grown straw. However, this conclusion is poorly supported statistically given the small number of samples used in the Mann Whitney U Test.

COMPARISONS BETWEEN DIFFERENT STRAW TYPES

1. Wheat was found to decay at a faster rate and reached a higher maximum CO₂ production level more quickly than barley and rice.
2. Barley was found to generally have decay rates in between those of wheat and rice.
3. Rice was found to decay at a lower rate and reach a lower maximum CO₂ production than wheat and barley.

In making those conclusions, the standard deviation of the mean for the decay parameters overlap significantly, thereby making it difficult to make comparisons between straw types. Also, no significant difference was found between straw types when comparing the decay parameters variance. The rate of degradation was found to almost be significantly different; however the variance appears to be the result of the unusually high decay rate for sample 2.

4.3 Summary of Chapter 4

Chapter 4 has presented the results found using the method described in Chapter 3, followed by analysis of those results. Chapter 5 will summarise the results and analysis from Chapter 4.

5 Summary

This chapter presents conclusions from the research findings, with reference to the objectives stated in Chapter 1. Also included are limitations found to this study and further research that is needed in the field of straw bale building.

5.1 Conclusions

Based on the decay parameters used in this study (maximum CO₂ production, time and rate of CO₂ production) variability was found between wheat, barley and rice straw. No significant difference was found between straw types when comparing the decay parameters. Although, visible interpretation showed rice straw was the slowest to decay, followed by barley, and wheat straw decayed the fastest. Although, visual interpretation of graphed results suggested difference in decay, statistical analyses found no significant difference (as indicated by large and overlapping standard deviations of mean values). As a result, the experiments conducted in this study are inconclusive in terms of whether different types of straw degrade at different rates. .

This study found no significant difference in degradation between organic and conventionally grown straw. However, the small sample size of the study does not provide a conclusive result. This study found no significant difference in decay between samples of the same straw type. Variance was found between samples, however due to the small sample size it was not found to be statistically significant.

What is clear from this study is that microbial decay of straw is a complex mix of variables. There is some evidence to show that the anatomical configuration of the plant can affect decay. Straw with less nodes and a longer stem wall provides physical protection from microbial degradation. Some evidence suggests that higher quantities of lignin and silica, particularly if located in the outer stem as a protective boundary, make straw more durable (Bigland & Prichard, 2005; Lindahl *et al*, 2006, p618). The quantity of N and the N:C ratio also appears to be able to affect the rate of decay of straw (Jenkins, 2005; Holzhueter, 2008). It is unclear, whether or not the farming method used makes any difference to the decay characteristics of the straw.

This study does not suggest conclusively if one straw would be more resistant to degradation than another straw, simply by considering the straw type. However, there is some evidence to suggest that rice straw is the most resistant to decay. A straw bale builder may be wise to adopt a broader approach to choosing straw, rather than just opting for the most available or inexpensive straw type. Other than straw type, a straw bale builder could consider;

1. Selecting healthy dry straw with a yellow rather than darker colour, to reduce the likelihood of straw already hosting a large, active microbial community;
2. Choosing a straw with high lignin and silica content (this could be determined by laboratory analysis);
3. Minimise grain heads in the straw; thereby reducing N content in the bales, which is a food source for microbes; and
4. Choosing straw with a low moisture content.

In terms of making straw bale buildings more durable, the choice of straw is just one variable that could affect decay of straw. Possibly more important considerations that can impact straw decay would be building design, detailing and maintenance.

5.2 Limitations of Research

This study was useful for investigating decay in straw bale buildings, however there were some limitations.

The small sample size used in this study has made it difficult to assess whether or not the samples are normally distributed. As a result, non parametric analysis was used, which was subsequently also limited in its effectiveness by the small sample size. Increasing the sample numbers would have made the results more statistically robust (Fowler *et al*, 1998).

The moisture content within the containers during experiments may not have been uniform. As a result, there may have been areas wetter or drier than the 160 % moisture content required. This may have produced areas with more or less decay. However, this non-uniform wetting and decay is likely to be similar to the conditions experienced in an actual straw bale building.

The gas analysers were reading O₂ levels at 15 % for the atmosphere; however the % of O₂ in the atmosphere is closer to 20 %. This suggests an inaccuracy with the gas analysers. However, for this study, the absolute % of gas is less important than the comparisons made between each sample.

The containers used in experiments were made from the semi permeable HDPE plastic. As a result, there was exchange of gases between the inside and outside of the container, which may have influenced the results. However, considering the same containers were used for all the experiments and that it was a comparative study, any minimal impact on gas concentrations would have been observed across all samples.

The short term nature of this study may not have simulated the movement of water in straw effectively. In this study, when I added water to the straw, it could enter four places: in the cells, in spaces between the cells, in the stem and on the surface. The water may not have had time to soak into the cells and may have sat primarily on the stem and surface. This may have affected the degradation characteristics of the straw. Water in a straw bale building has time to transfer into the cells of the straw.

The temperature and moisture content of straw in a straw bale building will be lower than in these experiments. As a result, the microbial activity would be different. Different microbes are active at different temperatures and moisture contents. Therefore, to extrapolate the results from this study to straw in a straw bale building is not accurately portraying the decay of straw in a straw bale building.

The short time frame of these experiments compared to the longer times generally required to create degradation within a straw bale building may chance the amount of decay that occurs. Generally, within a straw bale building, the straw will be at a lower temperature and moisture content than during these experiments, although it will be exposed for a much longer period.

The straw samples were exposed to a larger O₂ supplied environment than would be the case in a straw bale building. In a straw bale building, the straw comprises 10 % of the air space and the remainder is air. During these experiments the straw comprised approximately 1 % of the air space, leaving the remainder as air. As a result, the straw in the experiments was supplied with more O₂, which possibly enabled the microorganisms which favour aerobic conditions to be more active than anaerobic microbes. Also, the loose

straw used in this study allowed better access to oxygen than with whole straw stems. This may have affected the effectiveness of making comparisons with straw bale buildings.

Confounding variables were included in the straw samples which have made it difficult to analyse the results and make conclusions as to why one sample is different from another. For example, samples were collected from different years. As a result, samples grew in different seasons, with different temperature, rainfall, and harvest time, etc. All these confounding variables may have affected the decay characteristics of the samples, rather than the type of straw.

This study was not able to quantify the microorganisms present on the samples. Other studies have found that the effects of decomposition appeared to be related to the microbial population's presence at the start (Beare *et al*, 2002). A straw with a low population of microorganisms that decays more slowly than other straws is not necessarily more resistant to decay, there are just less microorganisms decaying it. Detailed knowledge about the microorganisms present could have indicated why a particular sample was decaying so quickly. Future experiments could sterilise the straw and then seed it with constant types and numbers of micro-organisms.

Having considered some of the limitations of this study, the next section looks at possibilities of future research.

5.3 Further Research

This study was largely inconclusive in regard to the decay difference between different types of straw. However, it is possible to do further research that would give more statistically robust conclusions. In future studies, sample numbers of 30 or more for each straw type would be more appropriate. This would allow the normal distribution of the samples to be calculated and parametric analyses to be completed. Once the sample size had been increased then any variance will be able to be located with particular samples or straw types. At that stage, having more information regarding any confounding variables would be useful. Such as differences in variety, season, location, soil, fertiliser used, pesticide used, the weather and the microbes present on the straw. To reduce the use of confounding variables, all samples could be collected in the same year, from the same region. And in this way, samples would have grown under the same weather conditions, and soil, thereby reducing variables. Having detailed information regarding these variables would enable the identification of why there is any difference between straw degradation. Being able to identify specifically why one straw decays faster than another enables a straw bale builder to possibly change that variable to obtain a more decay resistant straw.

Further research would be best to simulate the environmental conditions found in a straw bale building. The use of complex laboratory experiments simulating the conditions found in a straw bale building could be combined with ongoing post occupancy assessments of decay in actual straw bale buildings to provide long term evidence of the decay characteristics of straw. By simulating straw in a straw bale building a host of different variables need to be considered, such as the plaster used to cover the straw. Indeed, the influence of various types of plaster on the decomposition of straw in a wall is a subject that merits further study.

A further area of research, which could generate considerable controversy, is the possibility of developing genetically modified straw with decay resistant qualities; such as increased silica and lignin content and less nitrogen.

This study has confirmed the results found by Summers et al 2003, in which Summers was looking at straw storage and the risk of self combustion. As a result, this study is useful for future research concerning straw storage and the risk of self combustion. Different storage methods maybe appropriate for different straws in order to minimise the loss of straw to decay and spontaneous combustion.

6 Appendix

6.1 Calibrations

6.1.1 Gas Analysers

2 GA2000 gas analysers were used for this study, supplied by the Biology Department at the Centre for Alternative Technology, Wales, UK.

GA1: serial number GA05191 (new in 2000).

GA2: serial number GA05715 (new in 2002).

These analysers were made by Geotechnical Instruments (UK) Ltd, Sovereign House, Queensway, Leamington Spa, Warwickshire, CV31 3JR, England. Tel: +44 (0)1926 338111, Fax: +44 (0)1926 338110, Email: sales@geotech.co.uk, www.geotech.co.

CH₄, CO₂, measured by dual wavelength infrared cell.

O₂ measured by internal electro chemical cell.

An internal data logger was used and Data Field Comms software was used to download data to computer.

6.1.2 Weighting Scales

Use of durascale 100 scales: calibrated and accurate to 0.00.

Purchased from e-scales.co.uk.

6.2 Calculations

6.2.1 Drying of straw samples

Samples were dried and moisture content calculated according to the British Standards Institute (British Standards Institute, 2000).

6.2.2 Conversion % CO₂ into kg CO₂/kg dry straw

Using; $n = PV/RT$

Where,

P is absolute pressure of the gas (Recorded using GA 2000 gas analysers)

V is the volume of the gas (in liters, L)

n is the number of moles of gas (in moles, mol)(kg CO₂/kg dry straw)

R is the universal gas constant (which is $0.0820574587 \text{ L atm K}^{-1} \text{ mol}^{-1}$)

T is the absolute temperature (in Kelvin). 31 (lab temperature) + 273 .

I'm solving for the number of moles, so use $n = PV/RT$ (converting moles into kg/kg)

The use of CO_2 as an ideal gas. Because of CO_2 's relatively high boiling points, CO_2 obeys the gas laws only approximately. No actual gas perfectly conforms as an ideal gas under all conditions, however CO_2 is often considered an ideal gas. The ideal gas law is an equation of state. The state of an amount of gas is determined by its pressure, volume, and temperature according to the equation: $PV = nRT$

6.3 Other Data

6.3.1 Method

(pilot study)

Pilot 1: The aim of this pilot study was to compare the results produced from the two GA 2000 gas analysers, GA1 and GA2 respectively. Both gas analysers were connected to the same container. The above method was run over an 87 hour period. Results show near identical recordings of gases for both gas analysers (see Appendix A3). As a result, GA1 and GA2 were subsequently presumed to provide comparable results.

Pilot 2: The first aim of this pilot study was to test for leakage of gas between the inside of the container and the outside atmosphere. Expired air (breath) with its different gas concentrations (see section 2.3) was used to fill a container. The air was monitored to see if CO_2 and O_2 concentrations returned to atmospheric levels. It was found that the air gradually returned to atmospheric concentrations over 91 hours. The reason for the gas transfer was expected to be from leaks around seals and through the semi-permeable HPDE plastic used. The semi-permeable properties of HPDE were considered most suitable for these experiments for it was hoped to reduce excessive pressure building up in the containers, which may have caused seals to rupture. Also, the ability of some oxygen to enter the container and maintain aerobic microorganism activity was seen as creating a situation similar to straw in a straw bale building. This pilot study showed the permeability of the containers was unlikely to negatively impact the decomposition of samples.

The second aim of Pilot 2 was to try a different type of plastic container, changing from HPDE (high density ethylene) plastic to PET plastic. It was found to be more difficult to seal the PET plastic bottles and that this added to the rate of gas transfer between inside and outside of the container. As a result, HDPE was chosen in subsequent experiments as the container type for the method.

Pilot 3: The aim of this pilot study was to undertake a control to determine whether CO_2 and other gas concentrations would change without the presence of straw. The experiment was set up identically except no sample was put into the container. No change was found to the

gas concentrations in the container and therefore it was presumed that the addition of straw samples was generating any observed change in gas concentrations.

Pilot 4: The aim of this pilot study was to reduce gas transfer between the inside and outside of the container. Firstly, Ceresit 10B High Performance Silicone, a different silicon sealant, was used to improve the seals around the perforations in the plastic container. Secondly, an additional plastic bag was placed over the entire container and sealed in an attempt to further minimise gas leakage. Both the different silicon sealant and the addition of an additional plastic bag resulted in less gas transfer between the inside and outside of the container.

The first control (expired air) allowed leakage to occur throughout the experiments, however this occurred very slowly and the subsequent changes in atmospheric concentrations changed many orders of magnitude greater than the change through air leakage alone.

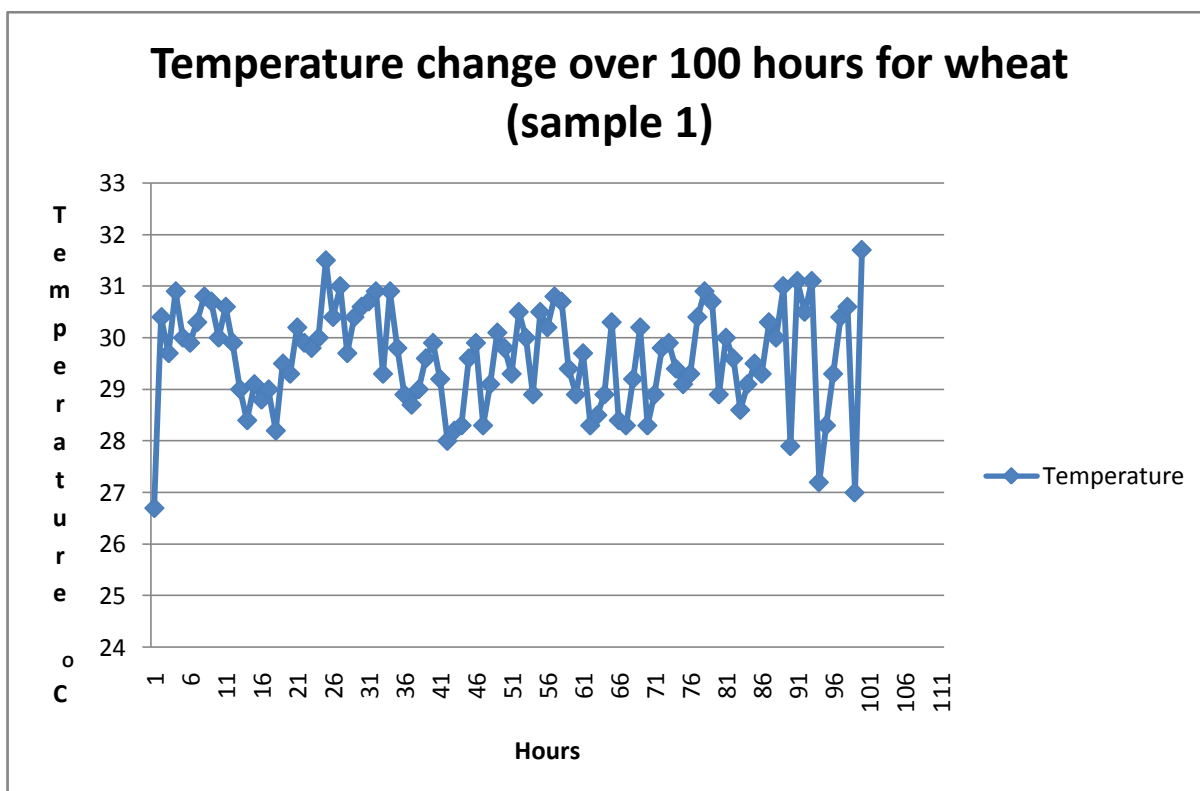
The second control results demonstrate that the containers were sealed adequately.

6.3.2 Results

Raw data list, including gases, temperature, pressure, etc. Including the CO and H₂S results from either sample 3 (pilot 6 ga1 30), sample 2 (pilot 11 ga1 49) or sample 5 (pilot 8 ga1 39).

Assuming an even distribution of carbon in straws organic constituents every 10 cubic centimetres of CO₂ evolved per gram of rice straw results from a 1.25% loss of organic matter (Summers, 2002, p8).

Temperature was recorded in every second sample container, with the Figure below showing an average result.



Justification for Temperature and moisture content chosen for experiments.

Appropriate temperature and moisture content were assessed from a variety of sources (Figure 1).

Temperature (°C)	Moisture Level (dry basis)(%)
20-70 degrees C microorganisms thrive (Summers, 2002)	Free moisture on surface is needed (Summers, 2002)
No dramatic difference found b/t 25 or 35 degrees C, although excess moisture at 35 caused problems (Summers, 2002)	Lots of activity > 70% mc Most activity at 158%mc (Summers, 2006)
Optimum temperature for decay is 30 degrees (Knight, 1997).	<30%mc, there was no measureable respiration (i.e. at 0-89 equilibriumRH) (Summers, 2002)
Greater than 23 degree C (Schwarzmueller, 2004)	Optimum RH for decay is 0.98 % (Knight, 1997).
30 degreeC is optimum (Wihan, 2007).	Greater than 90% (Schwarzmueller, 2004).

Figure 22: Justification for the Temperature and Moisture Content used in experiments (Knight, 1997; Schwarzmuller, 2004; Summers, 2002; Wihan, 2007).

Both wheat and rice; respiration at 30-40%mc and growth rate increased linearly to 100% mc (Summers, 2003). Start worrying about decay in straw if it is at 30% mc and above 5 degrees C for 30 days (Straube, 2006).

6.3.3 Analysis

WITHIN SAMPLES

Wheat: maximum C02 production

In respect to maximum C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.2683 suggests that there is little evidence of a significant difference between the medians (Figure).

Mann-Whitney Test and CI: sample 1 & sample 2: maximum C02 production.

	N	Median
sample 1	3	0.02100
sample 2	3	0.02800

Point estimate for ETA1-ETA2 is -0.00800
91.9 Percent CI for ETA1-ETA2 is (-0.04400,0.00501)
W = 7.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.2752
The test is significant at 0.2683 (adjusted for ties)

Wheat: time required to reach maximum C02 production.

In respect to the time required to reach maximum C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.0809 suggests that there is little evidence of a significant difference between the medians (Figure).

Mann-Whitney Test and CI: sample 1 & sample 2: time to reach maximum C02 production

	N	Median
sample 1	3	83.00
sample 2	3	33.00

Point estimate for ETA1-ETA2 is 50.00
91.9 Percent CI for ETA1-ETA2 is (33.00,66.00)
W = 15.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0809

Wheat: rate of C02 production.

In respect to the rate of C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.0809 suggests that there is little evidence of a significant difference between the medians (Figure).

Mann-Whitney Test and CI: sample 1 & sample 2: rate of C02 production

	N	Median
sample 1	3	0.00025
sample 2	3	0.00104

Point estimate for ETA1-ETA2 is -0.00079
 91.9 Percent CI for ETA1-ETA2 is (-0.00116,-0.00030)
 W = 6.0
 Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0809

Barley: maximum C02 production

In respect to maximum C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.1116 suggests that there is little evidence of a significant difference between the medians (Figure).

Mann-Whitney Test and CI: sample 3 & sample 4: maximum C02 production

	N	Median
sample 3	4	0.03350
sample 4	3	0.00900

Point estimate for ETA1-ETA2 is 0.02150
 94.8 Percent CI for ETA1-ETA2 is (-0.00701,0.04101)
 W = 21.0
 Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.1116

Barley: time required to reach maximum C02 production.

In respect to the time required to reach maximum C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.5959 suggests that there is little evidence of a significant difference between the medians (Figure).

Mann-Whitney Test and CI: sample 3 & sample 4: time required to reach maximum C02 production

	N	Median
sample 3	4	88.00
sample 4	3	58.00

Point estimate for ETA1-ETA2 is 17.50
 94.8 Percent CI for ETA1-ETA2 is (-39.01,37.02)
 W = 18.0
 Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.5959

Barley: rate of C02 production.

In respect to the rate of C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.0518 suggests that there is little evidence of a significant difference between the medians.

Mann-Whitney Test and CI: sample 3 & sample 4: rate of C02 production

	N	Median
sample 3	4	0.00038
sample 4	3	0.00016

Point estimate for ETA1-ETA2 is 0.00019
94.8 Percent CI for ETA1-ETA2 is (0.00007,0.00038)
W = 22.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0518

Rice: maximum C02 production

In respect to maximum C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.5926 suggests that there is little evidence of a significant difference between the medians.

Mann-Whitney Test and CI: sample 5 & sample 6: maximum C02 production

	N	Median
sample 5	4	0.01900
sample 6	3	0.01100

Point estimate for ETA1-ETA2 is 0.00350
94.8 Percent CI for ETA1-ETA2 is (-0.01200,0.02200)
W = 18.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.5959
The test is significant at 0.5926 (adjusted for ties)

Rice: time required to reach maximum C02 production

In respect to the time required to reach maximum C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.2159 suggests that there is little evidence of a significant difference between the medians.

Mann-Whitney Test and CI: sample 5 & sample 6: time required to reach maximum C02 production

	N	Median
sample 5	4	76.50
sample 6	3	44.00

Point estimate for ETA1-ETA2 is 15.50
94.8 Percent CI for ETA1-ETA2 is (-45.02,68.01)
W = 20.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.2159

Rice: rate of C02 production

In respect of the rate of C02 production the conclusion is that we cannot reject the null hypothesis at the 5% level of significance. The p value of 0.8597 suggests that there is little evidence of a significant difference between the medians.

Mann-Whitney Test and CI: sample 5 & sample 6: rate of C02 production

	N	Median
sample 5	4	0.00026
sample 6	3	0.00024

Point estimate for ETA1-ETA2 is -0.00003
94.8 Percent CI for ETA1-ETA2 is (-0.00019,0.00011)
W = 15.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.8597

BETWEEN SAMPLES

Straw: maximum C02 production

Anova: Single Factor for maximum C02 production.						
Summary						
Groups	Count	Sum	Average	Variance		
wheat	6	0.166	0.027667	0.000233		
Barley	7	0.172	0.024571	0.000229		
Rice	7	0.121	0.017286	8.99E-05		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000376	2	0.000188	1.038809	0.375284	3.591531
Within Groups	0.00308	17	0.000181			
Total	0.003457	19				

Straw : time required to reach maximum C02 production

Anova: Single Factor for time.						
Summary						
Groups	Count	Sum	Average	Variance		
Wheat	6	357	59.5	795.9		
Barley	7	522	74.57143	359.619		
Rice	7	464	66.28571	764.5714		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	741.9071	2	370.9536	0.588011	0.566338	3.591531
Within Groups	10724.64	17	630.8613			
Total	11466.55	19				

Straw : rate of C02 production

Anova: Single Factor for rate.						
Summary						
Groups	Count	Sum	Average	Variance		
Wheat	6	0.003707	0.000618	2.17E-07		
Barley	7	0.002167	0.00031	1.9E-08		
Rice	7	0.0018	0.000257	4.55E-09		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.79E-07	2	2.4E-07	3.327643	0.060315	3.591531
Within Groups	1.22E-06	17	7.2E-08			
Total	1.7E-06	19				

Mann-Whitney Test and CI: organic & conventional: maximum C02 production

```

N      Median
organic      7  0.02800
conventional 13  0.02100
Point estimate for ETA1-ETA2 is 0.00500
95.2 Percent CI for ETA1-ETA2 is (-0.00901,0.01900)
W = 84.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.4054
The test is significant at 0.4047 (adjusted for ties)

```

Mann-Whitney Test and CI: organic & conventional: time

```

N      Median
organic_1    7  46.00
conventional_1 13  83.00
Point estimate for ETA1-ETA2 is -17.00
95.2 Percent CI for ETA1-ETA2 is (-45.00,10.01)
W = 62.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.3834
The test is significant at 0.3830 (adjusted for ties)

```

Mann-Whitney Test and CI: organic & conventional: rate

```

N      Median
organic_2    7  0.00031
conventional_2 13  0.00026
Point estimate for ETA1-ETA2 is 0.00011
95.2 Percent CI for ETA1-ETA2 is (-0.00004,0.00071)
W = 88.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.2673

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