AN ASSESSMENT OF THE FEASIBILITY OF QUALITY INDICATORS FOR THE POSTHARVEST DETERIORATION OF SUGARCANE (*Saccharum officinarum L.*)

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Submitted in fulfilment of the requirements
for the degree of PhD

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December 2014

PREFACE

I ..Milindi Sylver Sibomana.. declare that

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ACKNOWLEDGEMENTS

My sincere gratitude goes to God for allowing me to complete this project, as well as to all that guided and inspired me to complete this endeavour.

- Prof CN Bezuidenhout, Prof TS Workneh and Dr N Sobratee from the University of KwaZulu-Natal and Dr. S Rutherford from South African Sugarcane Research Institute (SASRI), for their commitment to supervising the project, ensuring that a suitable standard was met and the work was also enjoyed.

- Prof PWL Lyne (SASRI), for his support and insights throughout the project.

- Seelan Naidoo and the Cane Testing Service (CTS) for the quality data and guidance.

- The staff and students in the disciplines of Bioresources Engineering, Hydrology, Plant Pathology, Horticulture and Crop Science at the University of KwaZulu-Natal, Pietermaritzburg, who provided support and shared their laboratory facilities. All colleagues who facilitated data analysis.

- All members of the SASRI Integrated Production Systems project for various insights provided. Dr. Brian Purchase for guidance on industry issues.

- Prof. MJ Savage, from the discipline of Agrometeorology at the University of KwaZulu-Natal, Pietermaritzburg, for providing technical support during the collection of environmental data.

- To my family for your love, support and encouragement throughout my degree, your words of wisdom and love sustained me. My friends in Pietermaritzburg, Kigali and beyond for walking this journey with me.

DECLARATION OF PUBLICATIONS

Details of contribution to publications and conference presentations that form part and /or include research presented in this thesis:

Sobratee, N, Sibomana, MS, Workneh, TS and Bezuidenhout, CN. 2014. Internode-specific susceptibility of sugarcane to post-harvest changes during harvest-to-crush delay in the KwaZulu-Natal Midlands. Part I: Green whole stalk cane. *Zuckerindustrie*. 139(8): 508-513. (Co-author, experimental design, experimental data collection)

Sibomana, MS and Bezuidenhout, CN. 2013. Statistical evaluations of sugarcane quality, deterioration and the impacts of weekend logistics in a commercial sugarcane supply chain. *Zuckerindustrie,* 1 (138): 30-35. (Main author, data collection and statistical analysis)

Sibomana, MS, Bezuidenhout, CN and Lyne, PWL 2011. Analysis of the Felixton integrated supply and production system with an emphasis on cane quality. *Proceedings of the South African Sugar Technologists' Association*, 84: 182-184. (Main author, data collection and statistical analysis)

Sibomana, MS, Sobratee, N, Bezuidenhout, CN and Workneh, TS. 2013. Postharvest deterioration of sugarcane in simulated harvest-to-crush-delays. *20th SAAFoST Biennial International Congress and Exhibition*, 7-9 October, Pretoria, South Africa. (Main author, data collection and statistical analysis)

Sibomana, MS, Bezuidenhout, CN and Workneh, TS. 2012. A review comparing postharvest technology in the South African sugarcane and fresh produce industries. *7th CIGR International Technical Symposium and 2nd International Conference on Postharvest Technology and Quality Management,* 24-29 November, Stellenbosch, South Africa. (Main author, literature compilation and critical review)

DEDICATION

Eternally grateful to you Lord for your enduring grace, I thank you for the loving family that I have been blessed with.

ABSTRACT

Sugarcane deterioration remains one of the most important supply chain efficiency leverage points in the South African sugar industry. Cane quality has been identified as an issue that has the potential to improve the overall efficiency of the sugarcane supply chain. A review comparing the postharvest quality management systems and measurements in the South African sugar and fresh produce industries was conducted. The difference in postharvest handling between the two industries was found to be an important factor dictating quality management. Advances in non-destructive quality measurement techniques and sanitation strategies were found in the fresh produce industries, which could be adopted by the South African sugar industry.

An empirical study of standard sugar industry cane quality parameters was also performed. Sugarcane quality parameters measured at the Felixton mill were analysed, *per ward,* using quality control charts and non-parametric statistical approaches. A daily analysis of these parameters, as well as the *Pol % Fibre* ratio, using Shewhart quality control ($\bar{\bar{x}}$) charts revealed that, overall, Monday deliveries were of significantly lower quality (P<0.01). This is a quantitative indicator of logistics (or management) inefficiency over the weekend. Using the Mann-Whitney test, *Pol % Fibre* was used to generate a grower performance index, based on high levels of statistical significance (P<0.05), which may allow stakeholders to improve operations, through identifying the levels at which individual growers deliver significantly (P≤0.05) lower quality cane in the early part of the week. This study uncovered new and significant statistical trends within the sugar industry's quality database and demonstrates the potential of *Pol % Fibre* as an indicator of quality inferiority in the cane supply chain.

To further investigate cane deterioration in this context, two burn/harvest-to-crush delay trials involving two sugarcane varieties (N12 and N31), which were exposed to ambient environmental conditions for a period of nine days after harvest were performed. On sampling dates, each variety was tested for quality parameters such as total bacterial counts, D-lactate production, and respiration. Standard sugar industry quality parameters and *Pol % Fibre* were also monitored. Parameters were measured in bottom, middle and top portions of the stalks to evaluate the effect of section on the parameter changes. Trial 1

was conducted on unburnt cane in October 2012 and Trial 2 on burnt cane, April-May 2013. Stalk portion significantly (P<0.001) affected the parameters, with the top and bottom portions showing higher bacterial proliferation, respiration rates and D-lactate production compared to the middle portion in Trial 1. Trial 2 showed no significant variability in stalk portion. In Trial 1, a significant (P<0.05) declining trend was noted for *Brix % DM* and *Pol % Fibre* in the top portion. The effect of higher respiration in the cut-ends in Trial 1 was noted in significantly reduced *Pol % Fibre* in these cut-ends. Environmental conditions were found to be the major factor influencing quality during the cane storage period. The study concludes, from both analysis of CTS data and the results of the BHTCD trials, that *Pol % Fibre* can be monitored at sugar mills as an additional parameter for signalling inferior quality and deterioration of cane consignments.

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ABBREVIATIONS

BHTCD: Burn Harvest To Crush Delay

CA: Controlled Atmosphere

CFU: Colony Forming Units

CTS: Cane Testing Service

DAC: Direct Analysis of Cane

DAFF: Department of Agriculture Forestry and Fisheries

EW: Electrolysed Water

FW: Fresh Weight

IMS: Integrated Mill Sanitation

IRGA: Infra-Red Gas Analysis

MA: Modified Atmosphere

MAP: Modified Atmosphere Packaging

MGB: Mill Group Board

NIRS: Near Infra-Red Spectroscopy

PPECB: Perishable Products Export Control Board

PROKON: Product Control for Agriculture

QCC: Quality Control Chart

RH: Relative Humidity

SDW: Significantly Deviated Weeks

TSA: Tryptone Soy Agar

TSS: Total Soluble Solids

TT: Thermal Time

VOC: Volatile Organic Compound

1. INTRODUCTION

Sugarcane (*Saccharum officinarum L.*) is one of the most economically important crops grown in South Africa, cultivated primarily in the KwaZulu-Natal, Mpumalanga and Eastern Cape provinces. The South African sugar industry makes a significant contribution to the economy creating employment in sugarcane production, transport and sugar processing. However, in this industry, sugarcane deterioration has been noted as a problem that has an impact on efficient sugar recovery in the factory, as well as overall sugar quality (Clowes and Wood, 1978; Lionnet, 1986; Lyne and Meyer, 2005; Eggleston and Harper, 2006; Walford and Nel, 2010).

Deteriorated cane may also point to sub-optimal infield and logistical operations, which eventually drain profits from the industry's bottom line (Ravno and Purchase, 2005; Martin 2008). This is why, over many years, researchers have been trying to establish a measure of deterioration severity (Wood, 1976; Lionnet, 1986; Bacci and Guichard 1994; Lyne and Meyer, 2005; Eggleston and Harper, 2006; Eggleston *et al.*, 2008; Petit *et al.*, 2009). The lack of the inclusion of a deterioration parameter in the South African cane payment formula (Martin, 2008) does not incentivise stakeholders to improve operations.

Deteriorated cane has a significant impact on recovery and processing activities in the mill. For example, due to the production of dextran, a product of the microbial degradation of sucrose, the mill faces increased viscosity, reduced evaporation and crystallisation, and clarification challenges (Cox and Sahadeo, 1992; Ravno and Purchase, 2005; Eggleston *et al.*, 2008). The overall reduction in milling efficiency results in negative outcomes for the entire sugarcane supply chain (Loubser, 2005; Walford and Nel, 2010).

Some of the factors that influence the postharvest deterioration of sugarcane in South Africa, include, climatic conditions, extension of the milling season into summer months when ambient temperatures and humidity are high, extended time lag between harvest and milling, crop ratoon, degree of mechanical damage and microbial infection, pre-harvest burning and delay between burning and harvesting, billet size as well as maturity status of the crop at harvest (Loubser, 2002; Perry *et al*, 2007; Eggleston *et al.*, 2008; Solomon, 2009). It is important to note that the climatic conditions in some of the cane-producing

regions in South Africa differ significantly. For example, in the Midlands and coastal areas of KwaZulu-Natal humid conditions are prevalent while in Pongola, Northern KwaZulu-Natal, drier conditions are prevalent and hence a need for irrigation for cane production. According to Morel du Boil *et al.* (2005) the *Leuconostoc* bacteria (primarily *Leuconostoc mesenteroides*) are the main microbial agents of postharvest deterioration in humid areas, while fungal microorganisms are prevalent in postharvest deterioration in the drier areas. This is important because there will be different metabolic products in the cane from the action of these microorganisms.

Leuconostoc mesenteroides, as an agent of microbial deterioration, has been the subject of a number of studies in the South African sugar industry. A significant amount of research has been performed on the metabolites of the *L. mesenteroides* infestation of sugarcane after harvest (Wood, 1976; Lionnet, 1986; Ravno and Purchase, 2005; Perry *et al*., 2007). These metabolites include dextran, mannitol, ethanol and lactic acid (Ravno and Purchase, 2005; Petit *et al.*, 2009; Walford and Nel, 2010) which have also been studied in attempts to develop indicators for rapid detection of deteriorated cane at the mill.

Dextran, for example, which appears to be a major problem in the South African sugar industry, still presents a challenge with regards to the rapid measurement of this polysaccharide at the mill (Eggleston *et al*., 2008). Walford and Nel (2010) reported mannitol as a possible indicator of cane deterioration, however, using a rapid enzymatic method for measurement was found unsuitable for South African conditions. Eggleston and Huet (2012) found mannitol and dextran to be more sensitive indicators compared to D-Lactic acid and acetic acid. The assessment of such biochemical indicators of deterioration is challenging because the responsible *Leuconostoc* species uses different degradation mechanisms under different environmental conditions (Walford and Nel, 2010) and hence the number and amount metabolic products may vary.

A number of authors have also reported on the advanced influence of microbial-induced deterioration in burnt cane compared to unburnt cane (Eggleston *et al*., 2008; Watt and Cramer, 2009). Dymond (1924), conversely reported that burning cane prior to harvest results in (a) the inactivation of enzymes that are involved in the degradation of reserve materials, and (b) killing microorganisms on the cane surface. Dymond (1924) therefore

argues that burnt cane deterioration relies on the invasion of extraneous microorganisms, whose advent is dependent on prevalent climatic conditions (Dymond, 1924).Furthermore, according to Wood (1973), the burning of cane prior to harvest results in smaller differences in deterioration rates among varieties, because of the reduced rate of sucrose inversion, initially, in burnt cane.

Green (unburnt) cane harvesting in South Africa is practiced by a smaller portion of growers to avoid the challenges associated with pre-harvest burning (Muller and Coetsee, 2008; Eggleston *et al*., 2008). However, due to the labour-intensive nature of green cane harvesting (Muller and Coetsee, 2008) mechanical harvesters are often used and often results in harvesting of billets rather than whole-stalk cane (Muir *et al*., 2009). In 2008, an estimated 15 % of the crop was mechanically harvested and billeted (Eggleston *et al.*, 2008). The deterioration rate of billets has been reported to be faster than whole-stalk cane (Wood, 1976; Meyer, 1997; Singh and Solomon, 2003). Singh and Solomon (2003) reported 5.33 % higher weight loss in billets compared to whole-stalk cane, combined with a significantly higher decline in recoverable sugar, juice pH, purity and significantly higher dextran and reducing sugars content in billets compared to whole-stalk cane stored in ambient field conditions for 7 days. Wood (1976) reported similar findings, and noted that under hot, humid conditions billeted cane exhibited losses of up to 28 % recoverable sugar within 4 days of cutting. From the literature it is apparent that when harvesting billeted cane, it is imperative to reduce the harvest-to-crush-delay to the minimum period possible, Singh and Solomon (2003) suggest 24 hours.

Currently, the sugar industry in South Africa is plagued by delays between harvesting and milling. This problem is contributed to in part by transport inefficiencies (Sanjika, 2013), cutter unavailability after burning (Kadwa *et al*., 2013) and intentional delays by growers who believe that the recoverable value increases with time after harvest (Lyne and Meyer, 2005). This observed increase in recoverable value may be because of the estimation of sucrose (for calculating recoverable value) by measuring *pol* in delivered cane samples, this may provide false high *pol* values due to dextran formation (Uppal, 2003; Naqvi *et al.*, 2014).The recoverable value (RV) cane payment system (Groom, 1999; Wynne, 2009) rewards high sucrose and penalises growers for high fibre and non-sucrose in delivered consignments. During the harvest-to-crush delay, however, *sucrose % cane* (the percentage

of sucrose in a cane stalk) may appear to increase due to the decrease in cane mass, this may result in consignments with high RV values but which experience poor extractability in the mill. Since growers are paid according to RV % and tons delivered, the loss in mass results in less revenue for the growers (Lyne and Meyer, 2005) and the poor extractability affects milling negatively (Walford and Nel, 2010). Morel du Boil (1995) and Eggleston *et al.* (2012) have specifically reported on the negative effects of postharvest cane deterioration on sugar crystallisation. Since the impact of delays are experienced by the entire supply chain it is important for the industry to be able to measure deterioration in a manner that can account for the effect of the various factors that promote quality decline.

An increase in the Burn/Harvest to Crush Delay (BHTCD) may result in an increase in cane deterioration. According to Ravno and Purchase (2005) and Martin (2008), postharvest deterioration of cane results in estimated financial losses of ZAR 60 million per season, based on deterioration-associated sucrose losses of 1.4 to 2.2 kg per metric ton of cane. This value does not include the cost of reduction in exhaustion efficiency at the mill as a result of processing poor quality cane. The estimated BHTCD in South Africa, for the 2007-2008 milling season was 71 hours (van den Berg *et al.,* 2008). Various researchers have reported that a delay of 3 days in the crushing of harvested cane results in a loss of 1.0-3.0 units pol cane and also leads to a noticeable reduction in factory performance and sugar quality (Bruijn, 1966; Bhandari and Singh, 1986; Solomon, 2002).

In this study, it was considered advantageous to attempt to draw from the knowledge used to monitor postharvest quality in other agri-product industries. In the fresh produce industries, for example, there are more stringent requirements and policies in place for postharvest quality management. This is probably due to the fact that in addition to internal quality, a number of visual quality parameters are required and fresh produce is often stored and sold for a longer period after harvest (Boxall *et al.*, 2006; Ortmann *et al.,* 2006; Caleb *et al.,* 2012). However, based on the challenges experienced with BHTCDs in the sugarcane supply chain, poor quality cane may be delivered to the mill and hence the "perishability" of sugarcane becomes a concern.

1.1 Aim and Objectives of this Research

It is hypothesised that the postharvest deterioration of sugarcane can be assessed through measuring certain cane properties on arrival at the mill. The aim of this project was to develop an indicator for the postharvest deterioration of sugarcane in a South African sugar industry supply chain context and to further investigate this indicator in experimental BHTCD trials.

The objectives of this study were:

1. To conduct a comprehensive literature review comparing postharvest technologies in the fresh produce and sugarcane industries in South Africa and to identify potential methods that can be used to measure sugarcane quality after harvest.
2. To perform statistical analyses of Cane Testing Service (CTS) quality data from a South African sugar mill to detect trends in quality parameters, at ward-level, measured at the mill and identify potential indicators of inferior quality as a result of extended BHTCD.
3. To conduct statistical analysis of individual grower data, monitoring the potential BHTCD indicator, in an attempt to assess grower performance in a selected mill area.
4. To evaluate the postharvest dynamics in different stalk sections *viz.* bottom, middle and top.
5. To use the information from the analyses (of both CTS data and the BHTCD trial data) to assess the viability and suitability of the indicator of deterioration during the BHTCD.

It is important to be able to measure, or estimate, 'time-since-harvest' in the sugarcane supply chain. A comparison of postharvest technology in the South African fresh produce and sugar industries is presented in the next chapter (Chapter 2), in an attempt to understand the current state of postharvest quality management in these industries and identify techniques that may be applicable to the sugarcane supply chain. Chapter 3 describes the methodology used in data collection and statistical analyses from both the Felixton mill as well as the BHTCD trials. In Chapter 4 the results will be presented and

discussed. The conclusions, recommendations for industry and future research will thereafter be presented in Chapter 5.

2. A COMPARISON OF POSTHARVEST TECHNOLOGY IN THE SOUTH AFRICAN SUGARCANE AND FRESH PRODUCE INDUSTRIES

2.1 Introduction

Agricultural products are affected by losses in quality and quantity between harvest and consumption (Kader 1992; Lyne and Meyer, 2005; Ansorena *et al.,* 2012). These products, for example bananas, avocados, tomatoes, lettuce, spinach, peppers, pome, citrus and stone fruit, are living tissues, subject to changes after harvest, which may affect quality at consumption (Kader, 1992; Wills *et al.,* 2007). Consumption in the context of this document also includes points in the value chain where the harvested produce is processed, because the quality of the produce is often a limiting factor in the processing operation (Solomon, 2000; de Souza Sant'Ana *et al.*, 2008). The diversity in morphological structure, composition and general physiology of produce, dictates that commodity requirements and recommendations for maximum postharvest life will vary among these produce (Wills *et al*., 2007; Yun *et al*., 2012).

According to Artés *et al.* (2009), the post-harvest life (and quality) of fresh-cut plant commodities, such as fruit and vegetables, is influenced by (a) pre-harvest factors, such as produce varieties and cultivation conditions, (b) processing factors, such as pre-cooling, trimming, peeling, disinfecting and drying, and (c) operation and distribution conditions, such as temperature, relative humidity and atmosphere conditions. It is apparent that a number of the factors mentioned by Artés *et al*. (2009) also affect sugarcane postharvest quality. Because of these varying factors, it is recommended that these agricultural commodities are processed under highly integrated systems, where holistic consideration is given to interactions between the many factors in the system (Shewfelt and Prussia, 1993; Artés, 2004; Artés *et al*., 2009).

Generally, the approach to postharvest quality management in the fresh produce and sugar industries is markedly different. Different approaches are contributed to partly by the differences in postharvest handling of sugarcane versus fresh produce commodities, the

impracticability of storing cane in controlled environments, the fact that the period between harvest and processing of cane is supposed to be minimal, as well as the fact that the majority of sugarcane in South Africa is burnt prior to harvest. However, there are some quality attributes that are of interest in both industries; for example sucrose content, total soluble solids, moisture content and dry mass. This justifies a comparison of postharvest technologies in these industries, in particular technologies that are used for measuring these quality attributes. In the next section, an overview of the sugarcane and fresh produce supply chains in South Africa is presented in order to facilitate an understanding of both systems.

2.1.1 An overview of the South African sugarcane supply chain

The South African sugar industry is globally competitive and involves interaction between growers, who produce the sugarcane, and millers who convert the cane into raw and refined sugars, syrups, specialised sugars and a range of by-products (Martin, 2008). According to DAFF (2011), the South African sugar industry generates an annual average direct income of ZAR 8 billion.

The sugarcane supply chain in South Africa, as depicted in Figure 2.1, consists of a number of parties involved in growing, harvesting, transporting and milling the produce (Perry and Wynne, 2004). Temporary storage of the produce *e.g.* at a transshipment zone, or as stockpiles at the mills is often practiced (Perry and Wynne, 2004; Bezuidenhout, 2010). In general, however, it is desirable to reduce the burn-harvest-to-crush delay (BHTCD) to a minimum (Solomon, 2009).

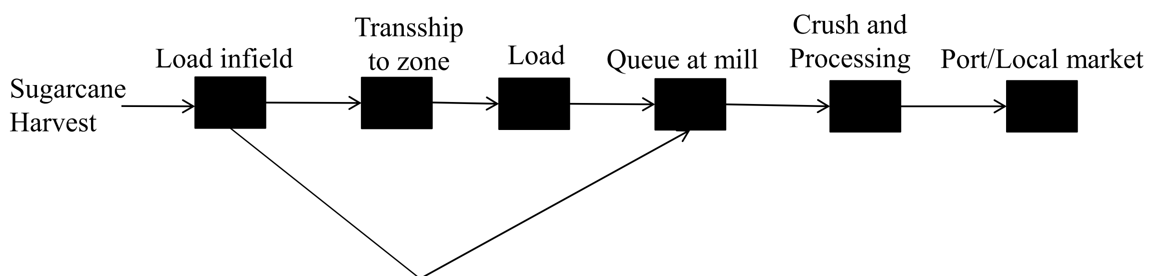


Figure 2.1 A typical South African sugarcane supply chain (adapted from Perry and Wynne, 2004).

An important role player in the South African sugarcane supply chain is the Cane Testing Service (CTS), which is under contract to individual Mill Group Boards (MGB) and is responsible for determining the quality of cane consignments for payment purposes (Anonymous, 2012a). CTS facilities are strategically located at the mills and have the potential to serve as check-points for sugarcane deterioration.

2.1.2 An overview of the South African fresh produce supply chains

In 2012, the South African fresh produce market was estimated to be worth ZAR 30 billion (Chikazunga and Paradza, 2012). The South African fresh-produce supply chains also involve a number of parties in the harvesting, transportation, storage, processing, marketing and retailing of the agricultural produce. One major difference between the sugarcane and fresh-produce supply chains is that long-term storage of fresh-produce prior to consumption is commonplace, whereas this is not the case in the sugar industry. Due to the cold storage requirement in this industry, the supply chain is often referred to as a cold chain (Ngcobo *et al.*, 2012). A simplified schematic of fruit/vegetable logistics in South Africa, as described by Ortmann *et al.* (2006), is presented in Figure 2.2.

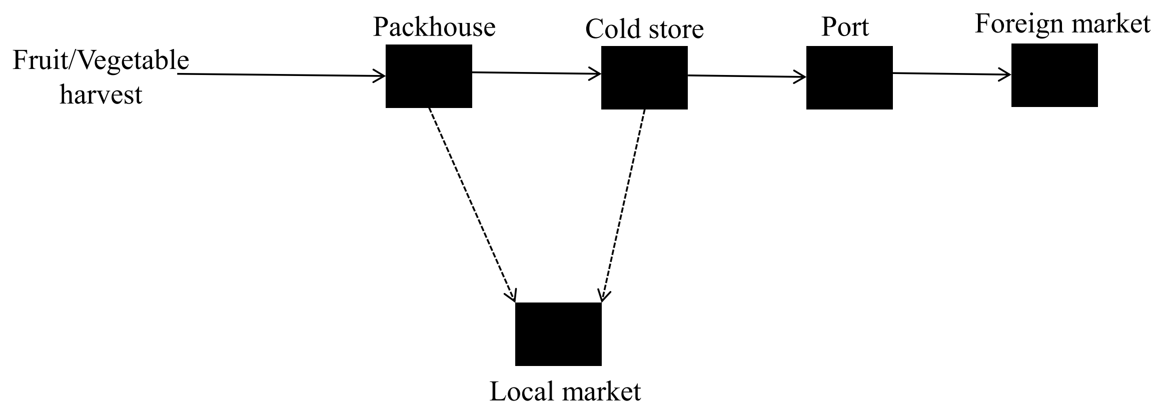


Figure 2.2 Simplified schematic of the fruit/vegetable supply chain in South Africa (adapted from Ortmann *et al.*, 2006).

In South Africa, the Perishable Products Export Control Board (PPECB) is responsible for the quality inspection and certification of a variety of perishable products that are destined for export (Julius, 2009). In some instances PPECB also provides quality inspection services for fresh produce destined for local consumption (Julius, 2009; Chetty, 2010).

PPECB provides a broad range of services from laboratory services measuring fresh produce quality, to equipment certification, standards and protocol management (Julius, 2009; Chetty, 2010). Product Control for Agriculture (PROKON) is another agency that performs quality certification of fruits and vegetables, mainly for local markets in South Africa (Anonymous, 2012b).

The aim of this review is to present selected postharvest techniques in both the South African sugar and fresh-produce industry, in an attempt to identify techniques for improving postharvest quality management in the sugar industry. This will be done by addressing the following objectives:

1. Identifying factors, common to both the sugar and fresh produce industry, which influence postharvest deterioration,
2. presenting an overview of how these factors are currently mitigated,
3. identifying internal quality parameters, measured in both these industries and briefly describing the analytical techniques used to measure these parameters, and
4. comparing these parameters and mitigation methods, in an attempt to identify opportunities for the South African sugar industry, this is presented in the discussion.

2.2 Factors that Influence the Postharvest Deterioration of Fresh Produce

A number of factors have been identified, by various authors, as being responsible for the deterioration of fresh produce after harvest (Kader, 1992; Shewfelt, 1993; Devereau *et al*., 2002; Farrell *et al*., 2002). According to Jayas (1995) and Devereau *et al*. (2002) harvested produce may be analogous to an ecosystem. They suggest that the interaction between physical, chemical and biological factors within this ecosystem leads to changes in the quality and nutritive value of agricultural products after harvest.

The postharvest deterioration of fresh produce is influenced by (a) biological factors such as respiration, ethylene (C_2H_4) production (both functions of the climacteric/non-climacteric nature of the produce), transpiration; (b) pathological breakdown from bacteria and fungi; (c) rodents and other pests; and (d) environmental factors such as temperature,

relative humidity and atmospheric composition (Kader, 1992). In this section some of the common factors that enhance deterioration of both sugarcane and fresh produce after harvest will be reviewed.

2.2.1 Respiration

According to Kader (1992), respiration is the process by which stored organic materials, such as carbohydrates, are broken down into simple end products with a release of energy. Oxygen (O_2) is used in this process and carbon dioxide (CO_2) is produced. A number of authors have reported the significant impact of respiration on postharvest quality of produce (for example Kader, 1992; Brosnan and Sun, 2000; Lyne and Meyer, 2005; Campbell and Klotz, 2006; Fugate *et al*., 2010).

The impact of respiration activity after harvest is evidenced in the depletion in food reserves of the fresh produce, which, according to Kader (1992), results in:

a. Hastening senescence, because of the exhaustion of food reserves which provide energy for the produce,
b. reduction in food value (in terms of energy) for the consumer,
c. loss of flavor quality, especially sweetness, due to reduction in carbohydrate content,
d. loss of saleable dry weight and
e. the generation of heat, this may create an optimum environment for postharvest pathogen proliferation, and also influences refrigeration and ventilation requirements.

Various studies have shown a correlation between the rate of postharvest deterioration of fresh produce and the rate of respiration (*e.g.* Brash *et al*., 1995; Paul *et al*., 1997; Chen *et al.*, 2010; Fugate *et al.*, 2010). The measurement of the respiration rate of fresh produce, under different environmental conditions, and over varying lengths of time after harvest, may provide valuable information to assist in managing (reducing) the respiration rate for maximum postharvest life (and quality).

The respiration rate of agricultural produce can be stated in terms of the rate of O_2 consumption or CO_2 production (Fonseca *et al.*, 2002). The following commonly used methods for measuring respiration rate in agricultural fresh produce are explained by Fonseca *et al*. (2002); (a) the closed or static system, (b) the flowing or flushed system and (c) the permeable system. In each of these non-destructive systems the gas concentration can be measured using techniques such as gas chromatography (for example Kader, 1992; Mahajan and Goswami, 2001) and infra-red gas analysis (for example Glover, 1973; Kader, 1992; Watt and Cramer, 2009).

In sugarcane research, Watt and Cramer (2009) relate the respiration rate in mature internodes to the postharvest deterioration of sugarcane. A closed system is used and CO_2 released from internode 10 is measured (Watt and Cramer, 2009). Postharvest sugar loss in cane stalks is often attributed to plant respiration (Lyne and Meyer, 2005; Watt and Cramer, 2009) and microbiological activity (Eggleston *et al.*, 2008; Watt and Cramer, 2009; Solomon, 2009), and by determining the respiration rate under different environmental conditions, estimates of the cumulative sugar loss as a result of microbial and plant respiration can be made and used to facilitate in the development of techniques to reduce this phenomenon (Watt and Cramer, 2009).

2.2.2 Transpiration

Transpiration affects the moisture content of agricultural products after harvest. Agricultural produce constantly lose water to the environment (Kader, 1992; Boxall *et al.*, 2002). In both the sugar industry (for example Lyne and Meyer, 2005) and the fresh produce industries (for example Brosnan and Sun, 2000), postharvest moisture loss has been identified as a challenge to postharvest quality. The postharvest loss of water from fresh produce is irreplaceable and leads to both quantitative losses, for example saleable weight, and qualitative losses, for example wilting, shrivelling and textural quality loss (Kader, 1992; Boxall, *et al.*, 2002; Caleb *et al.*, 2012). Moisture loss has been shown, by a number of researchers, to increase the susceptibility of harvested fresh produce to pathogen infection (Shewfelt, 1993; Boxall *et al.*, 2002; Sharma *et al.*, 2009). The transpiration rate of agricultural commodities is often measured during research, and moisture content is

measured as a quality parameter in both sugar and fresh produce supply chains (this is further discussed in Section 2.5).

2.2.3 Physical damage

Physical damage of harvested produce can significantly hasten deterioration (Kader, 1992; Solomon, 2009). The result of damage could be evidenced, for example, in browning of damaged tissues, acceleration of water loss, presentation of entry-sites for microbial infection (Eggleston *et al.*, 2008; Solomon, 2009) and stimulation of CO_2 and C_2H_4 production by the commodity (Kader, 1992). In South Africa, sugarcane burning before harvest (to ease manual harvesting) is a common practice and this results in physical damage and may lead to faster deterioration (Muir *et al.*, 2009). Physical damage also results in qualitative losses, especially in the fruit industry where appearance is an important factor.

2.2.4 Microbial spoilage

Bacterial and fungal activity have been identified, by many researchers, as an important issue in the postharvest deterioration of produce (Kader, 1992; Solomon *et al.*, 2000; Eggleston *et al.*, 2008; Solomon, 2009; Sharma *et al.*, 2009). Although microorganisms can infect seemingly healthy tissues, in many cases pathogen attack follows physical injury or physiological breakdown (Dymond, 1924; Kader, 1992; Kulkarni and Warne, 2004). Susceptibility to pathogen attack is enhanced by stresses such as chilling injury and sunscald (Kader, 1992).

The source of microorganisms responsible for deterioration may be at the preharvest, harvesting and/or postharvest stages. At the preharvest stage contaminated irrigation water and pesticide solution (Gemmel and Schmidt, 2012; Lopez-Velasco *et al.*, 2013) have been reported as a source of coliform bacteria and *Salmonella* which were detectable in fruit after harvest.

At harvest and during the postharvest period the origins of microorganisms responsible for decay include the handling, packaging and storage material used, especially, by small-scale

farmers (Adeoye et al., 2009; Kereth et al., 2013), sub-optimal hygiene conditions in the transportation equipment and pack-house (or factory) used by large-scale growers (Korsten, 2006). In the case of sugarcane during the harvest-to-crush delay specific ambient conditions have also been reported to support the proliferation of certain types of microorganisms. For example, humid conditions in the cane-growing Midlands and coastal regions of KwaZulu-Natal generally result in *Leuconostoc*-induce deterioration, while the drier Pongola region supports fungal-induced deterioration (Morel du Boil *et al.*, 2005). Furthermore, microorganisms have been reported as the main cause of postharvest deterioration in sugarcane with plant enzyme-induced degradation playing a lesser role (Eggleston, 2002).

2.2.5 Physiological breakdown

A number of physiological disorders in produce can occur as a result of preharvest and postharvest conditions (Kader, 1992; Strano *et al*., 2011). Examples such as freezing injury, chilling injury, heating injury, bitterpit and blossom-end rot have been identified (Kader, 1992; Strano *et al*., 2011). Bitterpit and blossom-end rot, for example, can be caused by a pre-harvest nutritional deficiency such as calcium deficiency (Kader, 1992). Storage conditions, in particular the temperature that commodities are exposed to will influence the occurrence of physiological disorders (in particular for freezing injury, chilling injury and heating injury). Sugarcane grown in the United States of America is also susceptible to freezing injury resulting in dead lateral buds (-4.4 °C) and freeze-cracks (-5.6 °C) (Eggleston *et al.*, 2004). The impact of freezes is enhanced if followed by warm, wet weather because this promotes microbial infection, leading to lower juice purity, higher acidity and polysaccharides such as dextran (Irvine and Legendre, 1985; Legendre *et al.*, 1985; Eggleston and Legendre, 2003). In the next section a brief description of environmental factors that influence deterioration is presented.

2.2.6 Environmental Factors

Environmental factors, *viz.* temperature, relative humidity and atmospheric composition, play a major role in postharvest quality. These factors influence the occurrence and rate of the biological factors of deterioration.

Temperature

Temperature has been determined as one of the most significant factors influencing the rate of deterioration in harvested commodities (Kader, 1992; Perry *et al.*, 2007; Watt and Cramer, 2009; Mashau *et al.*, 2012; Yun *et al.*, 2012). Temperature has been found to influence the emergence of many physiological disorders, determines conditions for pathogen proliferation and influences the effect of ethylene, the respiration rate, rate of moisture loss, as well as atmospheric composition in the storage environment (Kader, 1992; Caleb *et al.*, 2012). The control of temperature after harvest is therefore paramount to maintaining quality and extending storage life. Temperature control, common in the fresh produce industry, is not feasible in the South African sugarcane supply chain.

Postharvest sugarcane research has involved storing cane in controlled temperature environments (Perry *et al.*, 2007; Watt and Cramer, 2009) as well as storing cane in ambient conditions (Clowes and Wood, 1973; Smith, 1993; Lionnet and Pillay, 1988; Lyne and Meyer, 2005). The effect of ambient temperature storage (which is the method of sugarcane storage during the BHTCD in the industry) has been investigated focussing on the important microbial, biochemical, chemical, mass and moisture changes in sugarcane after harvest. (Lionnet, 1986; Lionnet and Pillay, 1988; Lyne and Meyer, 2005; Saxena *et al.*, 2010), it would also be of interest to monitor the change in respiratory behaviour under BHTCD conditions as was recommended by Lyne and Meyer (2005).

Relative Humidity

Relative humidity, defined as the ratio of the partial vapour pressure to the saturation vapour pressure, is a measure of the quantity of moisture held by air expressed as a percentage of what the air could hold at a particular temperature (Golob *et al.*, 2002). Moisture (water) loss from agricultural commodities is influenced by the vapour pressure deficit (VPD) between the commodity and the surrounding atmosphere (Kader, 1992; Medina *et al.*, 2012). The VPD is influenced by both temperature and relative humidity. Controlling these two factors is therefore critical in reducing the rate of water loss from commodities, as well as the microbial activity in the storage area (Boxall, 2002; Ansorena *et al.*, 2012).

The author was not able to find information on the effect of relative humidity on the postharvest microbial and plant respiration in sugarcane, as well as the impact of this on the industry cane quality parameters. This information might prove useful in defining postharvest activities in the sugarcane supply chain especially during warm and rainy seasons.

Gas Composition

The concentration levels of CO_2, O_2 and other gases in the storage environment are important determinants of the postharvest quality of commodities (Kader, 1992; Mahajan *et al.,* 2007; De Santana *et al*., 2011). As with many of the factors influencing deterioration, the influence of atmospheric composition is dependent on the commodity, cultivar, physiological age, temperature and duration of holding (Kader, 1992). For cane destined to the mill, the storage period is required to be minimal after harvest, and this might be the reason why no literature on the effect of atmospheric composition on harvested sugarcane could be found. However, atmospheric composition is important for packaging sugarcane for fresh consumption (Solomon, 2009).

2.2.7 Other factors

Certain agriculture commodities, such as potatoes, sweet potatoes, lettuce, peaches and strawberries, are affected by light during storage (Kader, 1992; Li *et al.*, 2007; Martinez-Sanchez *et al*., 2011). Effects, such as browning in lettuce and colour development in strawberries (Martinez-Sanchez *et al*., 2011) have been reported. The author was unable to find literature on light as a factor affecting sugarcane after harvest.

Other factors, such as the application of fungicides, growth regulators and produce maturity at harvest, may have an influence on the postharvest life of agricultural commodities (Kader, 1992; Watt and Cramer, 2009). It is, therefore, important to know what the impact of any implemented chemical may have on the quality of the harvested produce before application. In the next section an overview of the ways in which these factors are controlled is presented.

2.3 An Overview of Methods Used to Mitigate the Influence of Deterioration Factors

A number of techniques are currently in use for reducing the influence of the various deterioration factors on agricultural fresh produce quality after harvest. These techniques mainly focus on controlling the environmental conditions during storage, as well as preventing microbial proliferation on the commodity.

2.3.1 Temperature and relative humidity control after harvest

Temperature control is important during the postharvest storage of fresh produce. From the pre-cooling of the produce immediately after harvest to attaining and controlling an optimum temperature during storage (*cf.* Wills *et al.*, 2007). In South Africa's fresh produce industries, cold storage facilities are found at the ports and at various points in the fruit and vegetable supply chains (*cf.* Julius, 2009; Chetty, 2010; Cronje *et al.*, 2011; Mashau *et al*., 2012).

Temperature is controlled in the storage area to extend postharvest life by slowing metabolic activity after harvest and by suppressing the growth of pathogens. Examples of fresh produce that require cold storage include cv. Hass avocados, which are often stored at a safe temperature of 5.5°C (Snowdon, 1990; Kader and Rolle, 2004; Tesfay *et al*., 2011) and potatoes at 4°C (Kader and Rolle, 2004). Commodities that are not sensitive to chilling injury may be stored at temperatures as low as 0°C (Boxall *et al*., 2002), for example lettuce, spinach, carrots (Kitinoja and Kader, 2004; Workneh *et al*., 2011).

The South African sugar industry is faced with a challenge when it comes to temperature control after harvest. Although temperature plays a key role in sucrose loss after harvest, due to respiration, inversion and microbial degradation (Watt and Cramer, 2009), and the BHTCDs in most mill areas often exceed the recommended time for burnt cane *i.e.* 24 hours (*cf.* Solomon, 2009), the literature on storage temperature control in harvested cane is minimal. Solomon (2009) recommends storage of cane in small heaps and constant sprinkling with water, during the BHTCD, as a method to avoid high temperatures in the cane pile. It is important to beware of generating high moisture with this method, because

that may support microbial proliferation. Covering of harvested cane with trash was also recommended by Solomon *et al*. (2011) as a method for lowering the cane's temperature during the BHTCD. However, the findings of Eggleston *et al.* (2014) indicate the significant presence of *Leuconostoc* bacteria in the senescing brown cane leaves. Therefore, the trade-off in lowering the cane's temperature, by covering with trash, may be an increase in microbial infection and accelerate deterioration during the BHTCD. Boneta-Garcia and Lugo-Lopez (1962) suggest the storage of harvested cane in the shade as a means of keeping cool temperatures during BHTCD.

The regulation of relative humidity in the storage area is also important in reducing postharvest deterioration. Relative humidity in the storage area is highly dependent on temperature and as the air temperature decreases the relative humidity increases (Kader, 1992; Boxall *et al.*, 2002). A high RH store can be maintained by refrigeration in a store where moisture is added to the fans or a wet floor is maintained (Wills *et al*., 2007). The South African sugar industry faces a problem of moisture loss after harvest (Lyne and Meyer, 2005). This loss could be mitigated by developing structures that enable high RH conditions, such as evaporative cooling structures (Wills *et al*., 2007), which may not have to include refrigeration.

2.3.2 Atmospheric composition control in the storage area

Atmosphere management in storage areas is regulated by the use of a variety of techniques to create types of control systems referred to as controlled atmosphere (CA), modified atmosphere (MA) and modified atmosphere packaging (MAP) (Wills *et al.*, 2007). Controlled atmosphere refers to the precise control of the storage atmosphere composition, MA refers to a situation where the atmosphere composition is a function of the packing material or storage conditions and is achieved by the physiology of the tissue (Barkai-Golan, 2001; Wills *et al*., 2007). MAP refers to control of the storage atmosphere by selective permeability of the packing material (Wills *et al*., 2007). In South Africa all three technologies are used. Figure 2.3 is an example of MAP used in South Africa.

Figure 2.3 An example of pumpkin stored using MAP (Anonymous, 2012c).

According to Kader (1994), MA, CA and MAP in storage can be used to supplement optimum temperature and relative humidity maintenance in fresh produce quality preservation after harvest (during transportation and storage). In CA, MA and MAP storage the aim is to maintain low O_2 levels and increased CO_2 concentrations, both of which are produce-specific (Kader, 1994). The application of CA, MA and MAP technology appears to be limited with regards to sugarcane destined for sugar processing. However, in markets where sugarcane stalks are consumed fresh, vacuum packaging (a form of MA) may be used to maintain quality after harvest (Mao and Liu, 2000). This type of packaging limits the action of invertases and polyphenol oxidases (PPO) (Mao and Lin, 2000; Solomon, 2009). Figure 2.4 shows an example of packing peeled sugarcane billets in polyethylene bags for delivery to a local market in Liberia (Williams, 2011).

Figure 2.4 An example of fresh-cut sugarcane storage (Williams, 2011).

2.3.3 Sanitation

Biological deterioration as a result of microbial action is often enhanced by poor sanitary conditions during handling, in the storage area as well as during processing. These conditions often lead to poor quality produce and inefficient extraction of desired qualities during processing (Artés *et al.*, 2009; Solomon, 2009). Artés and Allende (2005) propose that the important considerations for the production of safe fresh-cut produce include screening materials entering the processing chain, suppressing microbial growth, reducing the microbial load during processing and preventing post-processing contamination.

To maintain the quality and safety of fresh-cut commodities, a number of sanitation strategies are used in various agro-industries, such as, antimicrobial solutions (Solomon *et al*., 2006; Artés *et al.*, 2009), O_3, UV-C light, intense light pulses and MAP under super-atmospheric O_2 (Artés *et al*., 2009), these are summarised in Table 2.1.

Table 2.1 Sanitation strategies used for preventing microbial contamination of agricultural commodities (adapted from Artés *et al*., 2009)

Strategy	Example	Physical Appearance	Examples of affected organisms	Further references
Antimicrobial solutions	Peryoxyacetic acid, chlorine dioxide, hydrogen peroxide, citric acid, ascorbic acid, calcium, electrolyzed water, steamer jet-injection, biocontrol	Liquid	*E. coli, L. monocytogenes, E. sakazakii*	Kulkarni and Warne, 2004; Rodgers *et al*., 2004; Rico *et al*., 2008; Solomon *et al*., 2011
UV-C radiation, intense light pulses			*P. aeruginosa, S. typhimurium, L. monocytogenes, S. enterica,* psychrotrophic coliform bacteria and yeast	Erkan *et al*., 2001; Allende *et al*., 2006
Ozone		Ozonated water	*S. typhimurium, E. coli, L. mesenteroides, S. aureus, R. stolonifer*	Zhang *et al.* 2005; Aguayo *et al*., 2006
Superatmospheric Oxygen		Gas	*C. lambica,* retards growth of anaerobes, *Enterobactericeae*	Escallona *et al.* 2007; Zheng *et al.* 2008

In a study of quality at a sugarcane factory, Antier (1996) emphasises that microorganisms which enter the factory in great numbers, such as mesophilic microbes, are not necessarily those that will multiply most in the factory, which in some cases maybe thermophilic microorganisms. To optimize sanitation programs, it is therefore important to instate a strategy that can reduce the population of the different microorganisms that present a threat to quality at different stages in the supply chain after harvest. Antier (1996), Solomon (2009) and Solomon *et al*. (2011) emphasise the importance of clean mills and an integrated mill sanitation (IMS) program. This involves the application of both chemical and physical treatments to facilitate the reduction in biological losses of sucrose at the mill.

The use of antimicrobial solutions appears to be common to both the sugar and fresh produce industries (Kulkarni and Warne, 2004; Artés *et al.*, 2009; Solomon, 2009; Solomon *et al*., 2011), for example, Sucroguard® (Kularni and Warne, 2004) has been used in South Africa and is applied to the cut-ends of sugarcane stalks after harvest. This has been reported to reduce invert sugars as well as the microbial count, however, it has not been widely adopted in the South African industry. In India, Singh *et al*. (2008) used glutaraldehyde and benzalkonium chloride solutions to reduce postharvest microbial and physico-chemical changes, which cause sucrose loss. The application of essential oil coatings, which have biocidal properties, on citrus has also been recommended for postharvest quality management, and serves as a replacement for synthetic fungicides (du Plooy *et al*., 2009).

Solomon (2009) recommends the use of electrolysed water (EW) fogging, to reduce purity decline and sucrose loss in sugarcane, both in the field (after harvest) and in the mill. This method has, reportedly, been used for disinfection of vegetables such as cabbage, spinach and lettuce (Wang *et al*., 2004). Ozonated water, which has been shown to increase shelf-life of grapes and tomatoes (Artés *et al*., 2009) appears to be ideal for sugarcane due to its effect on *L. mesenteroides*, a predominant microorganism in postharvest deterioration of sugarcane. However, the requirement for high purity water (Artés *et al*., 2009) may be a financial deterrent when attempting to apply this treatment on harvested cane at a large-scale. Ozone can also be applied in the gaseous phase for continuous or cyclic exposure. The cost of setting up a system for applying ozone, either in liquid or gaseous form to harvested cane, may impede the implementation of such a system (*cf.* Suslow, 2004), particularly due to the fragmented nature of the sugarcane supply chain, as well as the relatively low value density of the produce.

In both the sugar and fresh produce industries in South Africa, there are a number of parameters that are used to measure quality after harvest. In the next section these parameters will be identified and their measurement techniques described.

2.4 The Measurement of Quality Parameters in the Fresh Produce and Sugarcane Industries in South Africa

The determination of produce quality in the South African sugarcane and fresh produce supply chains is based on various parameters. These quality parameters may differ according to commercially desired attributes in the produce. In this chapter an attempt has been made to identify routinely measured quality parameters that may be of importance to both the sugar industry and the fruit and vegetable industries.

2.4.1 Quantitative measures of sugarcane quality parameters

In the South African sugar industry, the important sugarcane quality parameters are; sucrose, total soluble solids (TSS, measured as °Brix), moisture content, non-sucrose and fibre (Schaffler *et al*., 2003). Other indicators that have been suggested as indicators of deterioration include ethanol, dextran and mannitol (*cf.* Lionnet, 1986; Eggleston, 2008). The Recoverable Value (*RV*, expressed as a percent of cane mass), as described by Equation 2.1, is used as a basis for payment by the miller to growers (Groom, 1999; Wynne *et al*., 2009).

$$RV = S - dN - cF \tag{2.1}$$

where *S* is sucrose (*Sucrose % Cane*); an estimate determined by polarimetry, *N* is non-sucrose (*Brix % Cane - Sucrose % Cane*), *F* is fibre (*Fibre % Cane*), d is the relative value of sucrose from which each unit of non-sucrose diverts from sugar production to molasses and c is the loss of sucrose from sugar production per unit of fibre.

The coefficients c and d are determined each season (in 2012, c = 0.02 and d = 0.4 (Anonymous, 2012a)).

Pol, TSS, Nonpol, Fibre and Moisture

In the supply chain, the Cane Testing Service (CTS) routinely samples and analyses individual cane consignments using the Direct Analysis of Cane (DAC) system (*cf.* Schoonees-Muir *et al*., 2009), to determine *pol* (an estimation of sucrose), TSS, moisture

and fibre content. These values are required for the calculation of *RV* and to facilitate factory process control (Love, 2002; Martin, 2008; Anonymous, 2012a). *Pol*, in prepared cane samples and mixed juice, is measured in the factory by a method known as polarimetry, which represents an indirect measure of the sucrose content (*cf.* Schoonees, 2003). A polarimeter is used to quantify the amount of sucrose in a sample, by determining the angle of rotation of polarized light in the sample solution. However, as has been mentioned in the previous sections, this method of measuring *pol* is susceptible to providing false-positive readings, indicating higher values of *pol*, while actually measuring the optically active dextran polysaccharide (Uppal, 2003; Naqvi *et al.*, 2014).

The determination of non-pol content in the sugarcane is calculated as the difference between *Brix % Cane* and *Pol % Cane*. It is therefore important to measure the total soluble solids (°Brix) content of the sugarcane. In the South African sugar industry, the °Brix content is measured by the use of a refractometer (MacGillivray and Graham, 1969). *Purity* is another parameter determined from the °Brix and is measured as the ratio of *Pol % Cane* to *Brix % Cane*. In South Africa, the determination of *Fibre % Cane* is done indirectly from the °Brix and moisture values of prepared cane samples (*cf.* Schoonees-Muir *et al*, 2009). The moisture content of the cane is measured by the weighing of cane samples before and after drying. The value of the change in mass of the sample, is assumed to be the moisture content, this is calculated by Equation 2.2. The *RV % Cane* for individual consignments is then calculated from the adjusted DAC values upon direct determination of sucrose values obtained from gas chromatography tests (Walford *et al.*, 2004).

$$Moisture\ \%\ Cane = \frac{(Initial\ weight - Dried\ \ weight)}{Initial\ weight} \times 100 \qquad (2.2)$$

The presence (and concentration) of either ethanol, dextran, mannitol and/or lactic acid has been suggested (Lionnet, 1986; Smith, 1993; Eggleston *et al.*, 2008) as an indicator of sugarcane deterioration, but these products are not routinely tested in sugarcane consignments at South African sugar mills. This is because of a number of challenges such

as the inability to perform rapid identification and quantification, for example with dextran (Eggleston *et al.*, 2008) as well as the variability in ethanol production under different cane handling and storage conditions (Cox and Sahadeo,1992; Smith,1993). Figure 2.5 presents a summarized description (generic) of the process of sugarcane quality determination at sugar factories (mills). It is apparent, that deterioration indicators have not been incorporated into the process when determining quality for payment purposes.

Near Infra-Red spectroscopy (NIRS) is another technique that is gaining popularity as a rapid measure of sugarcane quality parameters in South Africa. NIRS in the South African sugar industry measures shredded cane and juice samples. This technology is able to measure a number of cane quality parameters, such as sucrose, fibre, °Brix, glucose, fructose, ethanol, lactic acid (*cf.* Meyer and Wood, 1988; Schaffler *et al.*, 1993; Edye and Clarke, 1996; Meyer, 1997; Naidoo and Simpson, 2011). Taira *et al.* (2013) have developed a technique for the non-destructive measurement of cane quality in stalks (particularly *Pol* and °Brix) using a portable Near Infra-Red spectrophotometer. Through the use of both reflectance and transmittance modes they were able to show the value of this instrument in in-field quality evaluation of stalks.

The detection of volatile organic compounds (VOC), such as ethanol, produced during deterioration, may also be performed using e-nose technology (Naidoo, 2003; Wilson and Baietto, 2009). Although not used commercially in the sugar industry, this artificial olfaction technology is currently used in quality control in a variety of food industries (Wilson and Baietto, 2009). In the South African sugar industry, the use of an on-line ethanol detector to signal deteriorated cane during processing has been investigated and recommended by Loubser *et al.* (2003).

However, as reported by Walford and Nel (2010), the metabolites such as mannitol and lactic acid, and fermentation products such as ethanol and dextran will vary in depending on the degradation mechanism with which the *Leuconostoc* species operates. This degradation mechanism varies with different environmental and storage conditions (Sahadeo and Cox, 1992; Walford and Nel, 2010). Therefore, for example, cane with low ethanol-high dextran content may not be detected by the e-nose or other on-line detection technology and to further compound the problem such a consignment may be considered to have a high *pol* value based on polarimetric measurements (Uppal, 2003).

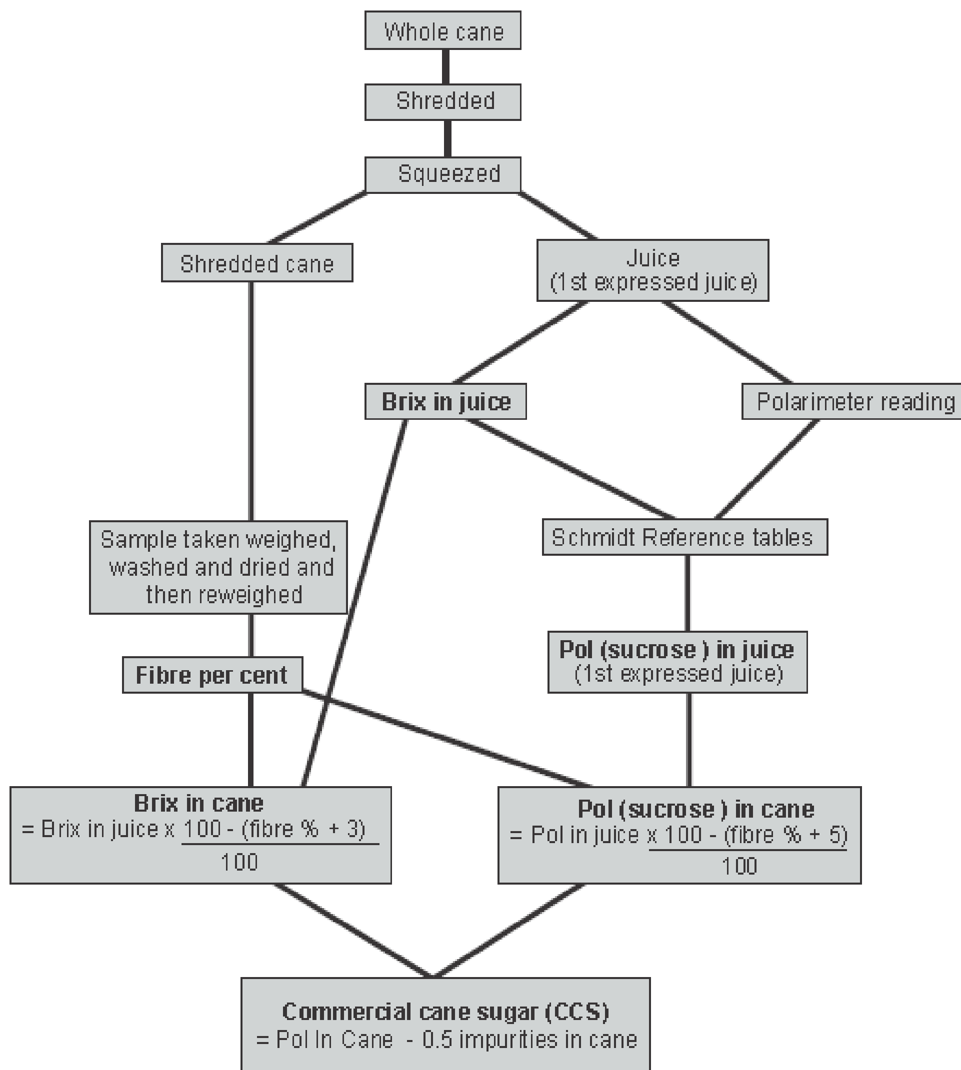


Figure 2.5 A process path diagram of sugarcane quality determination at a mill (Engelke, 2002).

According to Martin (2008), DAC methodologies are considered time-consuming and cannot be performed before the corresponding cane consignment is crushed. This time lag hinders the ability to objectively analyse cane quality before allowing the consignment into the factory (Lionnet and Gooch, 2002). Near Infra-Red (NIR) spectroscopy has therefore been used in recent times, as a faster alternative, to measure cane quality parameters (Naidoo and Simpson, 2011). The DAC methodologies are still popular with most sugar factories in South Africa.

2.4.2 Quantitative measures of fresh produce (fruit and vegetables) quality parameters

Quality measures in the fruit and vegetable industries differ slightly from the sugar industry, because, with the exception of produce destined for processing industries, fresh produce is delivered to a market that demands more detailed specifications with regards to the product desired. However, a number of the quality measures used in the sugar industry, such as sucrose, TSS, and deterioration indicators such as ethanol, are also used extensively in the fresh produce industry in South Africa (Swanepoel *et al*., 2007; OECD, 2009). In addition, pH appears to be an important indicator of fresh produce quality and is measured after harvest (Swanepoel *et al*., 2007). Instrumental and sensory evaluations are used in both research and commercial contexts, however, instrumental evaluations provide a common, and less subjective, standard (Abott, 1999).

In this section some techniques for measuring internal quality in fruits and vegetables are described. According to the OECD (2009) the internal quality of fruit is defined as: "the degree measured with objective criteria, to which a commodity has reached a sufficient stage of development such as to enable its quality, after harvesting and postharvest handling to be acceptable to the final consumer."

TSS, Titratable Acidity, Determination of Juice Content, Moisture Content, Dry Matter Content

The method of measuring Total Soluble Solids (TSS) is a destructive measurement of quality. Sugar is the main component of Total Soluble Solids (TSS) in fruit and vegetables (James and Ngarmsak, 2011). The measurement of TSS provides a reasonable indicator of sugar levels or sweetness (James and Ngarmsak, 2011). The measurement of TSS, as °Brix, in the fresh produce industry is similar to the sugar industry. This is performed using a refractometer or a hydrometer (*cf.* OECD, 2009). Sampling and sample preparation vary according to the commodity of interest (*cf.* OECD, 2009).

The sugar-acid ratio is used in the fresh produce industry as a measure of commercial and organoleptic quality (OECD, 2009). The methods described for determining pH are destructive. Sampling and sample preparation differs according to commodity (*cf.* OECD,

2009). Acidity is measured after harvest to calculate this ratio, which quantifies the quality of the fresh produce (James and Ngarmsak, 2011). Acidity can be measured by titrating a known volume of fruit juice with 0.1N NaOH to an end-point of pH=8.2 as indicated by phenolphthalein indicator or by using a pH meter (*cf.* Mitcham *et al.*, 1996; Abott, 1999; OECD, 2009; James and Ngarmsak, 2011). It should be noted that although Legendre *et al.* (2013) found pH to be an indicator of unburnt sugarcane deterioration, in many cases there has been poor sensitivity of pH and titratable acidity in indicating cane deterioration (Eggleston *et al.*, 2008).

The juice content of fruit, such as citrus and mango, is also an important parameter for measuring quality (Jha *et al.,* 2010). The process involves extracting as much juice as possible from the commodity and filtering this juice into a beaker (*cf.* OECD, 2009). To calculate the juice content Equation 2.3 is used.

$$Juice\ content\ (\%) = \frac{Total\ weight\ of\ juice\ (g) - Beaker\ weight\ (g)}{Total\ weight\ of\ fruit\ (g)} \times 100 \qquad (2.3)$$

Dry matter (DM) content is also an important indicator of quality after harvest in certain fresh produce commodities, such as kiwifruit, avocado, mango, apple and Swiss chard (McGlone and Kawano, 1998; Clark *et al.*, 2004; Daiss *et al.*, 2008; OECD, 2009). A popular technique for measuring dry matter content, involves measuring the mass of a sample of the commodity before and after oven-drying (*cf.* Devereau *et al.*, 2002; OECD, 2009). Equation 2.4, from OECD (2009), shows how the DM content is calculated:

$$DM\ (\%) = \frac{(C - A)}{(B - A)} \times 100 \qquad (2.4)$$

where A is the mass of the container, B is the total mass of the fresh sample and the container, and C is the total mass of the dry sample and the container.

The DM content is a useful indicator, because dry matter is dominated by a large carbohydrate component that is sugar and starch. Starch is converted to sugar on ripening

and after harvest (McGlone and Kawano, 1998; Clark *et al*., 2004). Therefore, DM content is an indicator of potential or actual sugar levels in the fruit (Clark *et al*., 2004).

Another important internal measure of quality after harvest in fresh produce is moisture content. A direct method of measuring moisture in fruit and vegetables is the oven-drying method (refer to Equation 2.2) (Devereau *et al*., 2002). Indirect methods, also known as secondary methods, in agricultural commodities were developed to overcome the time-consuming nature of standard methods (*cf.* Devereau *et al.*, 2002; Jha *et al*., 2011). These methods involve the use of specialised moisture meters to measure electrical properties of the commodity. Electrical properties correlate with moisture content and hence provide indirect estimates of moisture content (Devereau *et al*., 2002; Jha *et al*., 2011). Moisture meters have been used in the citrus (Fito *et al*., 2004) and grain industries (Jha *et al*., 2011). Another secondary technique, which is more accurate, but more capital-intensive, for measuring moisture, is Near Infra-Red spectroscopy (Devereau *et al.*, 2002; Nicolai *et al.*, 2007; Lin and Ying, 2009). Determining moisture content is of particular importance in dried fruit for example dried apples, pears, apricots, and grains (Devereau *et al*., 2002; Wittuhn *et al.*, 2005; OECD, 2009). Table 2.2 presents a summary of the discussed quality parameters.

Table 2.2 Comparison of internal quality parameters in the sugar and fresh produce industry

Internal Quality Parameter	Technique	Sugar Industry	Fresh Produce Industry
Pol/Sucrose	Polarimetry, High Performance Liquid Chromatography, NIR*	✓	✓
Total Soluble Solids (°Brix)	Refractometry, NIRS*	✓	✓
Fibre	Oven Drying, NIRS*	✓	✓
Moisture	Oven Drying, Moisture Meters*, NIR*	✓	✓
Dry Matter	Oven Drying	Not routine	✓
Volatile Organic Compounds (Ethanol *etc.*)	HPLC, GC, E-nose*	Not routine	✓
Acidity	Titratable Acidity, pH meter	Not routine	✓
Juice percentage	Determining mass of Juice as percentage of the fruit mass	Not performed	✓

*Non-destructive techniques. NIRS in the sugarcane industry in South Africa relies on destructive sampling.

2.5 Discussion

Research in postharvest technology appears to have generated more advances from the fresh produce industries when compared to the sugar industry. The requirements for quality from the fresh produce industries also appear to be more stringent and with more parameters, namely external quality parameters such as visual appearance, in addition to the internal quality parameters such as juice content and sugar/acid ratio. The majority of sugarcane grown in South Africa is destined for mill processing and therefore only internal

parameters such as sucrose content, fibre and moisture content are considered important in this industry.

Despite the frequent and excessive harvest to crush delays (BHTCDs) in the South African sugarcane supply chain, the literature on strategies implemented in the country to minimise deterioration during this delay period is still limited. Most literature that indicate advances in this area appear to point towards research conducted in the Indian sugar industry. However, the applicability of some these advances needs to be investigated in the South African context, to account for differences with the Indian sugarcane supply chain, for example the majority of cane in India is harvested unburnt (Franca *et al.,* 2012), unlike in South Africa.

The South African fresh produce industries show significant advances in storage technology, namely controlled atmosphere and modified atmosphere storage, as well as modified atmosphere packaging. This may primarily be due to the supply chain orientation of the fresh produce industries, which is designed to accommodate extended storage periods and long distance transportation of produce to consumer destinations. In the sugarcane industry, storage recommendations include techniques such as covering harvested cane with trash and sprinkling water periodically to maintain cool temperatures during the BHTCD.

In South Africa, the literature primarily shows attempts to identify chemical (or biochemical) indicators of deteriorated sugarcane and using these indicators as a basis for accepting or rejecting cane at the mill. Indicators such as ethanol, lactic acid and dextran have been used. However, advances in the sugar industry have called the reliability of some of these indicators, for example ethanol (Cox and Sahadeo, 1992; Smith, 1993; Eggleston *et al.*, 2008), into question. Ethanol is, however, also measured as an indicator of deterioration in citrus fruit. Nevertheless, it may also be important for these indicators (lactic acid, ethanol, mannitol) to be included in routine quality measurements of sugarcane at the mill, to facilitate signalling of deteriorated consignments.

Sanitation appears to be a concern in both industries. Antimicrobial solutions have been identified but are not widely used in South African sugarcane supply chain. These

solutions are widely used to mitigate microbial infection of fruit, after harvest, in South Africa. Integrated sanitation strategies suppress proliferation of the diverse range of microorganisms that are responsible for produce deterioration after harvest. Electrolysed water fogging of the cane in stockpiles is a technique that might prevent or reduce microbial action (Solomon *et al*., 2000; Solomon, 2009). The number of strategies that can be implemented in the sugarcane supply chain is limited by the costly nature of some of the treatments, such as UV radiation and intense light pulses.

Ideally, non-destructive measurement techniques would provide a rapid and accurate determination of quality. One such measurement is the indirect measurement of moisture content, based on the dielectric properties of the commodity. This technique, common for measuring moisture in grains during storage, has gained popularity in the citrus and apple industries (Devereau *et al*., 2002). Since moisture is an important parameter in the sugar industry, this non-destructive technique may prove useful to rapidly determine moisture content in cane stalks before processing. The use of infra-red thermography (IR) has proven useful in monitoring moisture content in citrus (Fito *et al*., 2004), however the application of this may be limited in sugarcane. Current work by Taira *et al*. (2013) shows the development of hand-held Near Infra-Red spectrophotometers for the non-destructive measurement of cane quality parameters and will be useful in measuring cane quality in-field and in stockpiles.

The use of artificial olfaction (Di Natale *et al.*, 2001; Naidoo, 2003; Brezmes *et al*., 2005) may prove useful in detecting volatile organic compounds produced during deterioration. In the South African sugar industry the major limitation to using this technology appears to be an inability to quantify these compounds, at the moment the instrumentation can only signal the presence of the volatile organic compound. In the future, with an integration of quantification ability, the e-nose could serve as a potentially powerful detector of deteriorated cane at the mill. Overall, Near Infra-Red Spectroscopy (NIRS) seems to be the most promising technique available in South Africa to measure sugarcane quality. With the incorporation of deterioration indicators in routine NIRS analysis of cane consignments, postharvest quality management may be improved.

The differences between the sugar and fresh produce supply chain, dictate the parameters that are important for each supply chain. The end product is often different with the sugarcane stalk not being visible to the consumer whereas most fruit and vegetables must be visually appealing to the consumer. However, it is important to compare internal quality parameters between the two industries, and advances in one industry may be applied to the other if possible and economically viable.

3. MATERIALS AND METHODS

This project was divided in two parts, part one involved the analysis of cane quality data from the Felixton Sugar mill, Felixton, KwaZulu-Natal and part two the generation of cane quality data from burn/harvest-to-crush-delay (BHTCD) trial experiments of whole-stalk cane in Pietermaritzburg, KwaZulu-Natal. The following sections describe the mill area, the data and statistical techniques used for analysing cane quality data from the Felixton Sugar mill.

PART ONE

3.1 Felixton Mill

The Felixton Sugar mill is located in close proximity to Empangeni, on the KwaZulu-Natal north coast of South Africa. Owned by the Tongaat Hulett group, it is the largest of their mills in South Africa. The mill was opened in 1984, following the consolidation of two smaller mills in the area *viz.* Zululand Sugar mill and the old Felixton mill (Renton, 1985). The mill was constructed to concentrate all the crushing capacity in a new and efficient establishment (Renton, 1985).

The Felixton mill was designed with a cane crushing capacity of 600 tons per hour through two identical extraction lines and an overall crushing capacity of 3.3 million tons of cane per annum (Renton, 1985). From May 2004 to December 2009, 11.67 million tons of cane were crushed at this mill. It is apparent that the mill is operating under capacity.

The construction of the mill was also influenced by a number of factors that were hampering efficiency in the production of sugar in the mill area for example cane handling and preparation, bagasse dewatering, bagasse depithing, pan boiling and crystallisation, overall energy balance, as well as the control and automation of the plant (Renton, 1985). Therefore, the Felixton mill was designed to achieve the following objectives:

- Minimum capital cost,

- lowest operating and maintenance costs,
- highest sucrose recovery,
- highest labour productivity, and
- least operational downtime

From the mentioned objectives, in particular the requirement for high sucrose recovery and least operational downtime, it is apparent that the issue of milling inefficiency as a result of poor cane quality would conflict with Felixton mill's design objectives.

According to the Cane Testing Service (CTS) records, provided in 2010, the Felixton Sugar mill had a supply base that consists of 5886 growers, located in 11 wards from cane areas inland as far as Melmoth (125 km) in the west and Mkuze (160 km) in the north (Anon, 2011a). This supply base includes large (32), medium (125) and small-scale (5729) growers, who supply mainly whole-stalk cane. Growers were classified according to average annual production, with small scale growers producing less than 1,000 tons per annum, medium scale between 1,000 – 10,000 tons per annum and large scale growers exceeding 10,000 tons per annum (*cf.* Armitage *et al*., 2009).

The suppliers use road and rail to transport the cane to the mill. Some of the growers own trucks and transport their own cane to the mill. The supply base consists of growers who rely primarily on either irrigation or rain-fed fields to produce the sugarcane. The Felixton mill supply chain is primarily constituted of three major groups of stakeholders, *viz*. the growers, the hauliers and the miller. Other parties who may play a role or influence decision-making in the system include the CTS, as well as the overarching sugar industry body, namely the South African Sugar Association (SASA). The system is fragmented to a certain extent (Gerwel *et al*., 2011), because the three major role players in the supply chain often operate in silos with negative consequences for the broader system. Cane quality was identified as a factor that has an impact on all stakeholders in the Felixton mill area (Sanjika, 2013). This, therefore, means that an improvement in cane quality management, for example, through quality monitoring/control, can be used to further integrate and increase efficiency in the Felixton sugarcane supply chain.

3.2 Quality Parameters

The characteristics of sugarcane quality parameters are important to consider when searching for cane deterioration related performance indicators. This is emphasised when searching for indicators that could point out the influence of management practices on cane deterioration. Deterioration and the behaviour of quality parameters differ when considering burnt versus unburnt cane, for example, unburnt cane results in more fibre per unit sucrose delivered to the mill (Bernhardt *et al*., 2000).

A number of cane quality parameters change quickly, and erratically, after harvest (*cf.* Lonsdale and Gosnell, 1976; Loubser, 2002), due to the inherent properties of these parameters. For example, the change in *Pol % Cane* after harvest will reflect a change in the numerator (*pol*), which is a substrate for microbial and physiological degradation, as well as in the denominator (cane mass), due to mass loss during respiration and moisture loss (Lyne an Meyer, 2005). This example shows that quality parameters based on *% Cane* (cane mass) as the denominator may not reliably indicate cane deterioration after harvest.

Fibre % Cane and *Pol % Cane* appear to be the slowest and fastest changing parameters, respectively, in cane after harvest (Lonsdale and Gosnell, 1976; Ravelo *et al*., 1991; Bacci and Guichard, 1994; Bernhardt *et al*., 2000; Loubser, 2002). It was, therefore, posited that a ratio of *Pol % Cane* over *Fibre % Cane* (*Pol % Fibre*) might be able to better represent the value of *pol* (sucrose) in the cane (particularly in the context of changing *pol* after harvest) and hence provide a better indicator of deterioration after harvest. Theoretically, this argument is valid because upon harvest no additional *pol* can be added to the cane once the photosynthetic mechanisms cease to operate (Wood, 1976; Mao *et al.*, 2006; Solomon *et al.*, 2006; Watt and Cramer, 2009). Simultaneously, fibre content is unlikely to change rapidly after harvest (de Robillard *et al.*, 1990; Loubser, 2002), since fungal degradation of stalk fibre (for example Breccia *et al*., 1997) has not been reported as a problem in the South African sugar industry.

3.3 Felixton Data Analysis

Cane Testing Service (CTS) provided sugarcane quality data for daily consignments at Felixton from 2004 to 2009. It should be noted that this data comprise quality parameters measured on whole-stalk cane consignments. Grower payment is based on the recoverable value (*RV*) system (refer to section 2.5.1). Table 3.1 provides a description of the parameters recorded by CTS.

Table 3.1 Parameters recorded by CTS.

PARAMETER	DESCRIPTION
Pol % Cane	The apparent sucrose content of any substance expressed as a percentage by mass, determined by single or direct polarization method.
Brix % Cane	Percentage by mass of dissolved solids in an impure sucrose solution.
Moisture % Cane	Percentage, by mass, of water in cane.
Fibre % Cane	Percentage of the water insoluble matter of cane from which the brix-free water has been removed by drying.
Ash % Cane	Percentage residue that remains after incineration.
Tons cane	Mass of sugarcane per delivery.
Time stamp	Date, delivery and crush times.
Farm and field number	Identification of farm and field for each delivery.

The parameters in Table 3.1, in the context of this study, were measured from prepared cane samples. *Pol % Cane* was determined by digesting a portion of the prepared (shredded) cane sample and the reaction of this digested sample with lead sub-acetate powder for clarification. The filtrate was added to a 200mm *pol* tube with a saccharimeter for measuring *pol* content, however, for the final *pol* calculation of the sample the °Brix is

also required (*cf.* Schoonees-Muir *et al.*, 2009). °Brix was measured by digesting a portion of prepared cane sample and filtering this portion, the °Brix of the filtrate was then measured using a refractometer (*cf.* Schoonees-Muir *et al.*, 2009). The moisture content of shredded cane samples was measured by the oven-drying method, which involved drying the samples at 105°C for 60 minutes and recording the difference in mass before and after drying (*cf.* Schoonees-Muir *et al.*, 2009). *Fibre % Cane* was determined indirectly from °Brix and moisture content (*cf.* Schoonees-Muir *et al.*, 2009). Ash content of prepared cane samples was determined by decomposing samples (after weighing) at 650°C for 45 minutes in a furnace, the mass of ash that remains was expressed as the percentage thermal ash on sample (*cf.* Schoonees-Muir *et al.*, 2009).

The CTS data consisted of 417759 deliveries, by 5886 growers, from 11 wards (growing zones), constituting a total of 11665913.4 tons of sugarcane. Due to the large sample size represented in the Felixton data it was important to select a representative sample that reflected a significant amount of the deliveries to the Felixton Sugar mill. The next section describes how the final sample size (used for this study) was selected.

3.3.1 Data selection – Pareto analysis

The Felixton Sugar mill data showed a supply base that consisted of 5886 growers. A large proportion of these growers are small-scale producers and deliver only a few loads of cane per season. The scale of production was based on the definition by Armitage *et al*. (2009). Small-scale growers were assumed to hinder efficient data analysis, because they have a small impact on the overall performance of the mill (and supply chain) and were hence removed from the analyses. According to Monczka *et al.* (2010) too much data, incorrect data and incorrect measures are among the challenges that face supply chain managers in measuring operational performance with suppliers. The Pareto principle was applied to identify an appropriate dataset (Leenders *et al.*, 2006). The Pareto principle states that the majority of the problems are often caused by a small percentage of the issues, also referred to as the 80:20 rule (Halteman, 2007). Pareto analysis is an important and widely used technique in supply base management (Leenders *et al.*, 2006). In this case, growers who delivered 80% of the cane to the mill, were selected for analysis. Montgomery (2009) supports this approach and states that quality cost reduction can be achieved through an

application of the Pareto principle. It is acknowledged that due to the nature by which cane is handled at the mill, blending of consignments in particular, even a small quantity of deteriorated cane may affect the extraction process significantly and this may justify the inclusion of small scale growers in the sample. However, small scale growers in the Felixton mill area were noted to not only supply low tonnage, but also have inconsistent deliveries, which would affect the statistical analysis. The consistency of deliveries from large scale growers was also one of the reasons for selection of this sample in alignment with the Pareto principle.

The distribution of the number of growers against the tons of cane delivered from 2004 to 2009 is shown in Figure 3.1. Growers are sorted according to their tons delivered. The growers who represent 80% of the deliveries to the mill are under the area shaded in grey (Figure 3.1). The growers were then grouped into 11 wards (growing zones as delineated by the Felixton extension officer and Mill Group Board). Where uncertain (ward could not be identified), the particular grower's data were removed from further analyses. The number of growers in each ward was not equal. Table 3.2 summarises the number of growers and tonnage from each ward, showing that in total 64.4% of the total tonnage delivered to Felixton from 2004 to 2009 was analysed. The data represent all wards that supply the Felixton mill.

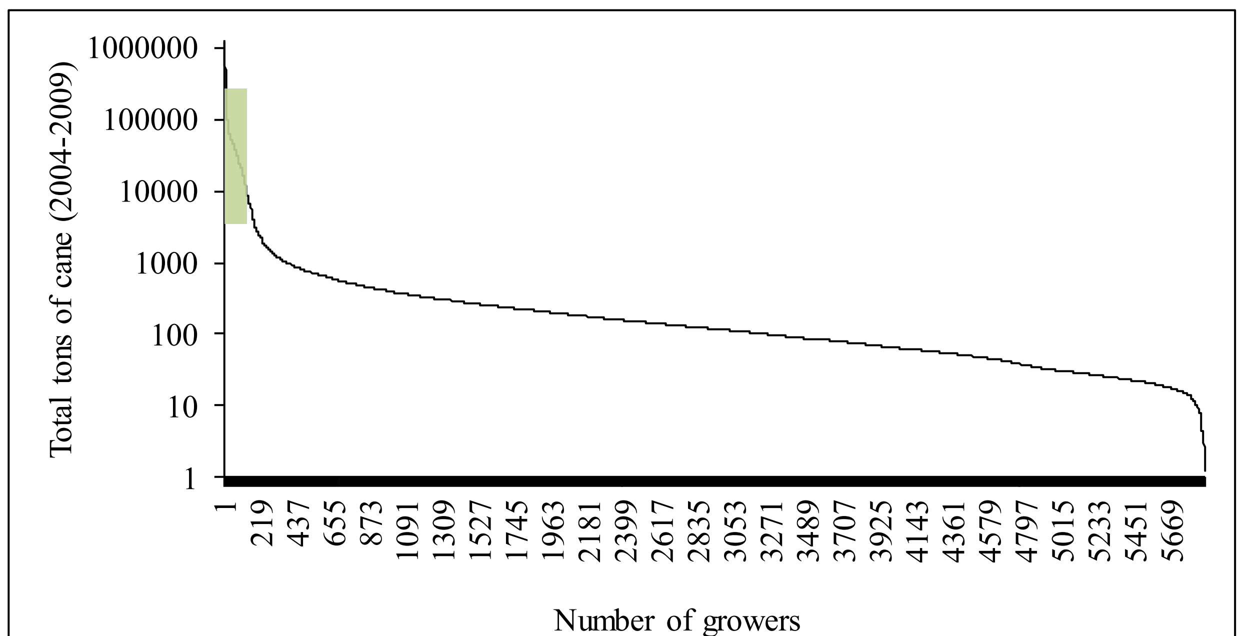


Figure 3.1 The distribution of grower size in the Felixton mill supply area, highlighting (shaded area) the growers who delivered the largest portion of cane from 2004 -2009.

Table 3.2 Number of growers whose data were used for analysis

Ward	Number of growers	Total tons of cane (2004-2009)	Percentage of Felixton mill tonnage (2004-2009)
Empangeni central	4	865091	7.4
Empangeni east	4	318004	2.7
Empangeni west	3	163409	1.4
Felixton flats	4	1665023	14.3
Felixton hills	6	435432	3.7
Heatonville riparian	3	126653	1.1
Heatonville scheme	10	901462	7.7
Mposa	6	456950	3.9
Mtunzini	7	545831	4.7
Nkwalini	5	248100	2.1
Northern areas	3	1790638	15.3

After the data selection, an exploratory statistical technique, known as statistical process control, and quality control charts in particular, was used to analyse the quality data by ward to determine if there were any cane deterioration trends that could be detected in the data. Further details of this technique are presented in the following section.

3.3.2 Quality control charts

Data analysis was performed within wards. It was assumed that cane delivered after the weekend might experience more deterioration because of slower weekend logistics. Cane deterioration due to weekend logistical problems has also been reported in the Indian sugar industry by Solomon (2009). Quality control charts (QCCs), a statistical exploratory method, were used for the initial analysis of industry quality data. QCCs were plotted for all six years, with the days of the week on the x-axis and the following parameters on the y-axis; *Fibre % Cane*, *Pol % Cane*, *Purity*, *RV % Cane*, *Nonpol % Cane* and *Pol % Fibre*.

QCCs are part of statistical process control. Statistical process control is the application of statistical techniques to monitor and control processes (Leenders, 2006; Montgomery, 2009). In any process, variation in output is inevitable. However, it is important to differentiate between two kinds of variation, *viz.* common-cause and special-cause variation.

Common-cause variation is due to inherent properties of the process itself. This type of variation cannot be altered without changing the process entirely because of, for example, the properties of a particular variety of cane. Special-cause variation occurs at a lower frequency than common-cause and is caused by an identifiable external factor. Special-cause variation, also referred to as assignable-cause variation, can for example be assigned to prolonged cut-to-crush delay. A process operating with only common-cause variation is statistically considered to be in control, whereas assignable causes of variation (beyond a defined level of tolerance) represent an out-of-control process (Montgomery, 2009). A QCC (or $\overline{x}$ chart), is a statistical technique that can be used to identify out-of-control processes in operations over a specified period (Ipek *et al*., 1999; Leenders *et al.,* 2006; Montgomery, 2009; Kaya and Kahraman, 2011).

In establishing a QCC, three main elements have to be calculated, *viz.* the (a) centre line (CL), (b) upper control limit (UCL) and (c) lower control limit (LCL) (Ipek *et al*., 1999; Montgomery, 2009). The CL (*cf.* Equation 3.2) represents the mean value of the quality characteristic equating to an in-control state. The UCL (*cf.* Equation 3.1) and LCL (*cf.* Equation 3.3) are horizontal lines above and below the CL, respectively. These lines delineate the region within which a process is in control (Montgomery, 2009). If a data point falls outside the control limits, it can be interpreted as proof that the process is out of control for that particular data point, and it demands investigative action to determine the assignable cause or causes responsible for this behaviour (Montgomery, 2009).

Designing a QCC involves noting the sample size, control limits and frequency of sampling (*cf.* Montgomery, 2009; Ipek *et al*., 1999). A general mathematical approach for a QCC (for data with variable sample sizes) is shown in Equations 3.1 – 3.3, where the parameters for a QCC for a hypothetical statistic *b* are calculated. In the equation $\overline{\overline{x}}$ is the average weighted mean for the entire population and $\overline{s}$ the standard deviation of the population mean (*cf.* Montgomery, 2009). A constant A_3, which depends on sample size n, is used to calculate the distance from the center line expressed in standard deviation units (Montgomery, 2009). The constants used when defining control limits for variable control charts are tabulated in Appendix 3.

$$UCL = \overline{\overline{x_b}} + A_3 \overline{s_b} \tag{3.1}$$

$$CL = \overline{\overline{x_b}} \tag{3.2}$$

$$LCL = \overline{\overline{x_b}} - A_3 \overline{s_b} \tag{3.3}$$

Where, $\overline{\overline{x_b}}$ is the average weighted mean for the entire population of *b*, $\overline{s_b}$ is the standard deviation of the population mean of *b* and A_3 is the multiplication factor of standard deviation of the mean, used to determine the control limit width.

The definition of control limits is important when designing a quality control chart. The width of the control limits are set inverse to the sample size *n*. The control limits should be defined in a manner that avoids *Type I* and *Type II* errors. *Type I* error (alpha error) occurs when the chart shows the process to be out-of-control when this is not the actual case, while a *Type II* error occurs when the process is determined to be in-control when in actual

fact it is not (Montgomery, 2009). In this study the control limits were designed such that the *Type I* error probability was 0.0027.

Each quality parameter was plotted on a separate QCC. For each parameter, the average values for each day of the week from 2004 to 2009 were plotted on the QCC. Each QCC therefore represented a particular quality parameter for a specific ward between 2004 and 2009. This enabled an exploratory analysis of quality parameters through the week at the ward level.

The next section describes the technique used to assess individual grower quality based on the trends observed from the exploratory analysis.

3.3.3 Statistical significance of trends in grower data

Based on the results from the exploratory analysis *Pol % Fibre* was selected as an appropriate indicator of cane deterioration (Table 4.1), showing that in a number of wards growers delivered inferior quality of cane in the beginning of the week. The unpaired Mann-Whitney test (*cf.* Noether, 1991), also known as the Wilcoxon-Mann-Whitney test, was used to analyse (by comparing) two sets of data for each grower, *viz. Pol % Fibre* on Sunday – Tuesday and *Pol%Fibre* on Wednesday – Saturday. The benefit offered by this method is that, as a non-parametric technique, it yields accurate estimates of the P-value even when the data is far from a normal distribution (McDonald, 2009). The Mann-Whitney test involved the comparison of each of the Sunday – Tuesday *Pol % Fibre* observations with those of the Wednesday – Saturday group and determined dissimilarity by calculating whether the observations were larger or smaller, when compared.

The research null hypothesis (H_0) for this section assumes the distribution of Sunday – Tuesday *Pol % Fibre* measurements is equal to Wednesday – Saturday *Pol % Fibre* data distribution. The alternative hypothesis (H_a) is that the two sets of data are not equal in distribution.

The two sets of data were analysed for each of the 55 growers for all weeks, from 2004 to 2009. The acceptable significance level for rejection of the null hypothesis was when $P \leq 0.05$. A new indicator was generated for each grower, referred to as the significantly deviated weeks percentage (SDW %). This was calculated as the percentage of weeks with

P-values ≤ 0.05 (H_0 rejected) in relation to the total number of weeks. For example, when a grower has a high SDW % value, it implies that he/she frequently delivered inferior quality cane during the beginning of the week.

Due to the difference in the number of deliveries amongst growers, it was important to not only determine whether the two sets of data were significantly different, but also to calculate the change in *Pol % Fibre* (Δ*Pol % Fibre*) for the weeks when significant difference was noted. The reason for this is that if a hypothetical Grower A has a large number of deliveries, then statistically Grower A may have a smaller standard error compared to Grower B with fewer deliveries. A small difference in the *Pol % Fibre* data sets would be reported as significant for Grower A, resulting in a greater SDW % allocation. A grower with fewer deliveries may be flagged as having a small SDW %, simply because of a larger standard error compared to the large grower, even if there is a substantial difference in his/her data sets. Therefore, it is important to assess grower performance from the values of both the SDW % and the change in *Pol % Fibre*.

In addition to the analysis of industrial data, two nine-day Burn/Harvest to Crush Delay (BHTCD) trials were performed in Pietermaritzburg, South Africa. A number of parameters, including *Pol % Fibre*, were monitored during these storage periods and the data collection techniques are presented in the next section.

PART TWO

3.4 Sample Storage and Environmental Monitoring

These experiments involved the generation and statistical analysis of laboratory data. Two varieties of sugarcane were harvested as whole-stalks, *viz.* N12 and N31, on the 15th of October 2012 (Trial 1) and 29th April 2013 (Trial 2). Both cane varieties are grown in the rainfed region of KwaZulu-Natal, this includes the Midlands area which was selected for proximity to the research site. The varieties were selected based on sample availability in Trial 1 and to ensure that the selected varieties were physiologically different. The literature shows that, in general, N31 has a high fibre:sucrose ratio, while N12 is classified as having a moderate fibre:sucrose ratio (Anonymous, 2006). The fibre content of N31 has

been estimated at 103 % of N12 (Anonymous, 2006). These two varieties can therefore be considered to be physiologically 102 different.

In both trials the cane was harvested randomly from different stools in a commercial plot and topped at the natural breakage point (estimated to be between internode 3 and 4; *cf.* van Dillewijn, 1952). Unburnt cane was harvested in Trial 1, whereas burnt cane was harvested in Trial 2. In Trial 1, both varieties were 23 months old (second ratoon) at the time of harvest, grown in Glenrosa (Soil Classification Working Group, 1991), whereas in Trial 2 the N31 was 18 months (fourth ratoon), while N12 was 23 months (first ratoon), grown in Westleigh (Soil Classification Working Group, 1991). In both trials, the cane was considered to have achieved sufficient maturity, as would be considered in the commercial cane supply chain.

The stalks were stored at the University of KwaZulu-Natal, Pietermaritzburg (29°37'39.72"S, 30°24'09"E, altitude of 671 m above sea level). The cane samples were stored as loose stalk-bundles (shallow piles), in attempt to simulate in-field storage. The cane was stored for a period of 9 days. The storage period was selected based on reported BHTCDs in the South African sugarcane industry. According to van den Berg *et al.* (2008) the South African sugar industry experiences an average BHTCD of 3 days. The storage periods were set at 9 days to monitor changes that might occur in an extreme BHTCD. Figure 3.2 shows the storage sites for the unburnt and burnt cane in Trial 1 and 2, respectively.

Figure 3.2 Storage sites for harvested cane, A is unburnt cane in October 2012 (Trial 1) and B is burnt cane in May 2013 (Trial 2).

During the BHTCD the air temperature and relative humidity were measured by a temperature and relative humidity probe (CS500, Campbell Scientific®, Utah, USA) placed in a 6-plate radiation shield 2 m above the ground. The environmental conditions were recorded hourly.

3.4.1 Sample preparation

It was assumed that cane deterioration is a function of time and symptoms progress gradually from the exposed cut-ends of the stalk. All tests were performed in a stalk-portion-specific manner to take this into consideration. On each sampling date, cane stalks were partitioned into bottom, middle and top stalk portions, each analysed separately for each parameter. A similar partitioning of cane stalks is noted in the studies by Rizk and Normand (1969) and Clowes and Wood (1978). Each set of lab samples involved 5 stalks of each variety, as replicates. The partitioning of cane stalks is presented in Figure 3.5.

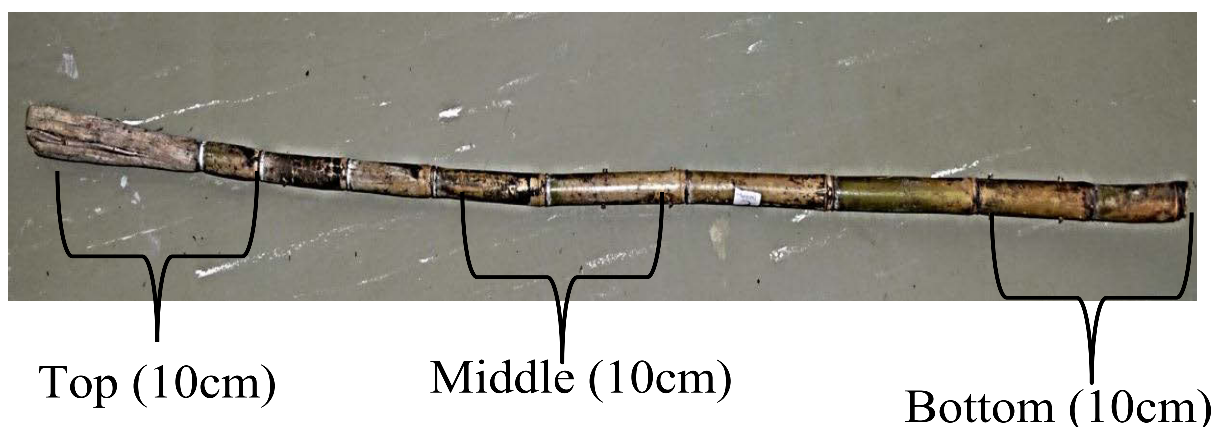


Figure 3.3 Partitioning of cane stalks for lab analysis.

3.4.2 Experimental design

The experimental design showing the frequency of sampling and replications is presented in Figure 3.6. It should be noted that for the SASRI mill room laboratory analyses each sample constituted of 12 stalks. This was done to facilitate the operation at the SASRI laboratory, which required larger cane mass for analysis. The experimental design includes variety, cane section *viz.* bottom, middle and top, and day as factors to be used in the data analysis.

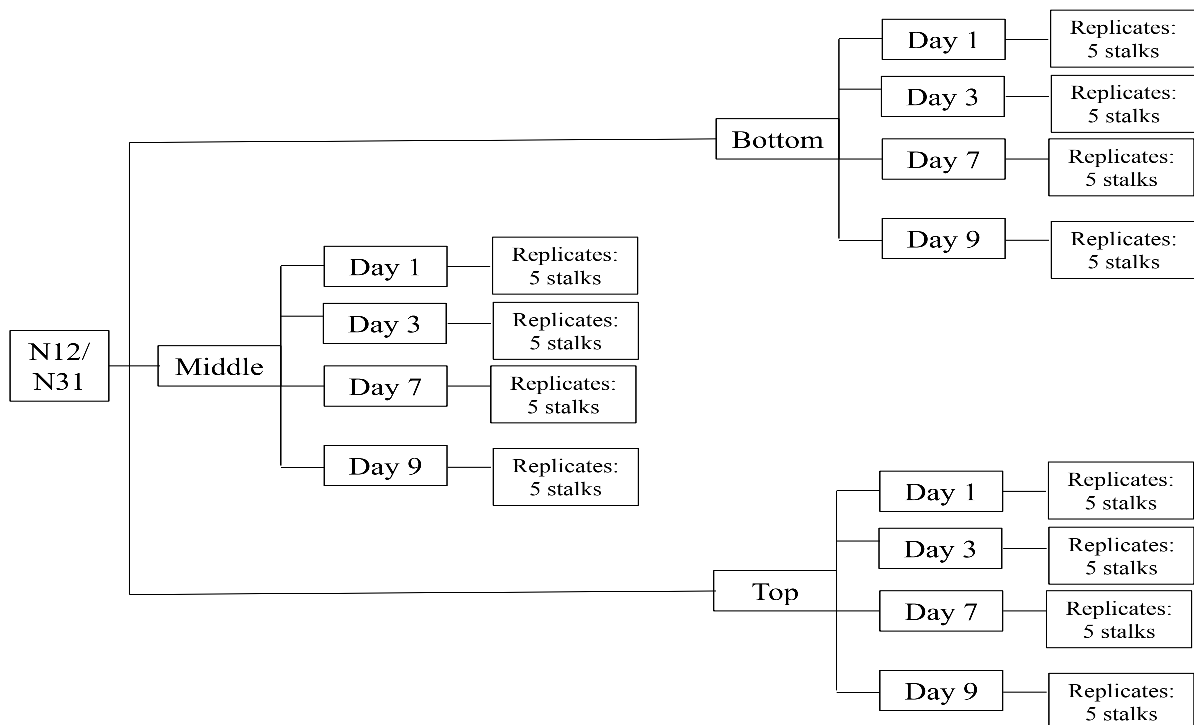


Figure 3.4 Experimental design followed in Trial 1 and Trial 2, on each sampling date five replicates were analysed for each variety.

The laboratory analyses consisted of microbiological, biochemical, physiological tests and mill room (industry quality parameters) analysis of harvested cane. The details of these tests are presented in the following sections.

3.4.3 Microbial and physiological assays

All sample analysis was as per the experimental design in Figure 3.6, and included (a) total bacteria colony counts, (b) lactic acid assays and (c) respiration measurements.

Total Bacteria Colony Counts

The harvested cane samples were subjected to microbiological assays, to determine the total population counts of bacteria during the storage period. Population determinations were done by standard plate counts with Tryptone Soy Agar (TSA) as the substrate medium (Margesin *et al*., 2011). The TSA media consisted of tryptone (15.0 g L^{-1}), soy peptone (5.0 g L^{-1}), sodium chloride (5.0 g L^{-1}) and agar (13.0 g L^{-1}). The TSA media was prepared to an adjusted pH of 5.5, which according to the literature is the natural pH of fresh sugarcane juice (Cavalcante and Dobereiner, 1988; Legendre *et al*., 2013).

The plate-count procedure was performed to determine populations of heterotrophic, aerobic/facultatively aerobic bacteria in the cane samples over the 9-day storage period. According to Eggleston *et al.* (2008), bacteria such as *Lactobacilli* and *Leuconostoc mesenteroides* are the most common microbial agents of cane deterioration in South Africa. Due to the unavailability of antibiotic chemicals, such as cycloheximide, the incubation period was minimised to strictly 48 hours and temperature at 28°C. All these conditions were set to mitigate the growth of cane-infecting fungi and yeast, which according to literature require longer incubation periods (Morais *et al.,* 1997; Marshall *et al.,* 1998; Cortes *et al*., 2006; Hauli *et al*., 2013). In addition observed colonies, were also studied microscopically to ensure that they were not yeast colonies.

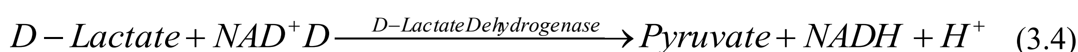
On each sample date, 0.1 g of tissue samples from the different stalk internodes were suspended in 9.9 mL of Ringer's solution and vortexed, making a 10^{-2} dilution. A serial dilution was performed by adding 1 mL of these vortexed solutions to 9 mL Ringer's solution, making a 10^{-3} dilution. Then, 0.1 mL of each dilution was spread-plated (Isaac and Jennings, 1995) in triplicates onto TSA plates. All handling of sample material was done following aseptic techniques to ensure no introduction of contamination to the samples or media. These were, then, incubated at 28°C for 48 hours, after which colony counts were performed (Martin, 2008) with the aid of a colony counter (Boeco, Colony Counter CC-1, Hamburg, Germany).

Lactic Acid Assay

The production of D-Lactic acid, through the measurement of D-Lactate concentration in sample solutions, was tested using an enzymatic bioanalysis/food analysis kit from R-Biopharm® (Roche, Mannheim) (Martin, 2008). D-Lactic acid is a metabolic product of the genus *Leuconostoc* bacteria from the fermentation of glucose (Garrity, 2001; Eggleston *et al*., 2004) . The stalk portions were crushed with a hammer. Then, 0.2 g of sample tissue was added to 1 mL of sterile distilled water in micro test tubes. The tubes were then vortexed and placed at 60°C, with agitation (100 rpm), for 45 minutes. To clarify the sample solution, the samples were centrifuged (10000 x g) for 10 minutes (Laborzentrifugen, 1-14 Sigma®, Osterode am Harz, Germany), the supernatant was then

transferred to new tubes and centrifuged again to remove any particulate matter (Martin, 2008).

The determination of D-Lactic acid in the cane samples was based on the principle described in Equation 3.4 below:



$$D-Lactate + NAD^{+} D \xrightarrow{D-Lactate Dehydrogenase} Pyruvate + NADH + H^{+} \quad (3.4)$$

The kit provided four reagents, Reagent 1 was Glycylglycine buffer, Reagent 2 was a nicotinamide adenine dinucleotide (NAD) solution, Reagent 3 was a glutamate pyruvate transaminase (GPT) suspension in ammonium sulphate and Reagent 4 was D-Lactate-Dehydrogenase. The assay involved measuring the absorbance of the sample in two steps, *viz.* Step 1: after the addition of Reagents 1-3 and Step 2: after adding Reagent 4. The change in these absorbance readings, at a wavelength of 340 nm, was used to calculate the concentration of D-Lactate in the sample solution in g L^{-1}, as well as in g $100g^{-1}$.

The measurement of changes in absorbance in the samples were compared to changes in a reagent blank (RB). The reagent blank for Step 1 comprised of 1000 µL sterile distilled water, 1000 µL reagent 1, 200 µL Reagent 2 and 20 µL Reagent 3, whereas the sample was 100 µL sample, 900 µL sterile distilled water, 1000 µL Reagent 1, 200 µL Reagent 2 and 20 µL Reagent 3 . The reagent blank and sample tubes were mixed well and incubated for 5 minutes at 21°C, after which the absorbance (A_1) was read in a spectrophotometer (Ultrospec II, LKB Biochrom™). After recording the absorbance readings, 20 µL of Reagent 4 was added into each of the sample tubes and the reagent blank tube. Each tube was mixed well and incubated for 30 minutes at 21°C, after which the absorbance was read (A_2).

The change in absorbance was determined by Equation 3.5:

$$\Delta A = (A_2 - A_1)_{sample} - (A_2 - A_1)_{RB} \quad (3.5)$$

where, ΔA is the change in absorbance readings at 340 nm.

Equation 3.6 was used to calculate the concentration of D-Lactate in the solution ($C_{D\text{-}Lactate}$ in g L^{-1}).

$$C_{D-Lactate} = \frac{(V \times MW \times \Delta A)}{(\varepsilon \times d \times v \times 1000)} \tag{3.6}$$

where V is the total volume (µL), MW is the molecular weight of D-Lactic acid (g mol^{-1}), d is the optical path (cm), v is the sample volume (µL) and ε is the extinction coefficient of NADH at 340 nm(6.3 ($Lmmol^{-1}cm^{-1}$)).

The content of D-Lactic acid in the solid samples ($Content_{D\text{-}Lactate}$ in g $100g^{-1}$) was then calculated by Equation 3.7:

$$Content_{D-Lactate} = \left(\frac{C_{D-Lactate}}{weight_{sample}}\right) \times 100 \tag{3.7}$$

Respiration Rate

The respiration rates of the specified stalk portions were determined in a closed system (Fonseca *et al.*, 2002) by Infra-Red Gas Analysis (IRGA) (Watt and Cramer, 2009). The respiration rate was measured with a respirometer (EGM-4, PP Systems®, Massachusetts, USA). The stalk portions were placed in sealed 350 mL containers. After a 20-minute incubation period the CO_2 concentration in the containers (gross CO_2) was measured in parts per million (ppm). The CO_2 concentration in an empty sealed 350 mL container (ambient CO_2) was also measured over 20 minutes. This technique is referred to as the measurement of respiration in a static system (Fonseca *et al.*, 2002; Saltveit, 2004). The difference between the gross CO_2 for each sample and the ambient CO_2 was recorded as the net CO_2 produced. The CO_2 production rate (C_{rate}) was calculated as per Equation 3.8 (Saltveit, 2004).

$$C_{rate} = \frac{P(CO_2) \times V}{(m \times t)} \tag{3.8}$$

Where, *P(CO_2)* is the net CO_2 produced in ppm, *V* is the headspace volume in mL which is the difference between sample volume and container volume, *m* is the sample mass in kg and *t* is the incubation time in hours.

3.4.4 Industry quality parameters analyses

In both trials, the total soluble solids (°Brix) as *Brix % Cane*, dry matter content as *DM % Cane*, *Pol % Cane*, *Fibre % Cane* of the stalk portions of interest were determined for each sampling day at the SASRI mill room laboratory, Mt Edgecombe, KwaZulu-Natal, South Africa. Cane samples were analysed by use of direct analysis of cane (DAC) techniques (Schoonees-Muir *et al.*, 2009) as well as Near Infra-Red Spectroscopy (NIRS) (*cf.* Schumann and Meyer, 2000). For each sample date, 12 stalks of each variety were cut into bottom, middle and top portions to be analysed as 1 sample for each portion. Frozen cane samples were delivered to SASRI where they were thawed, shredded and the tissue samples analysed.

For a description of the DAC techniques for the quality parameters refer to section 3.2. It should be noted that the NIRS instrument at SASRI (Matrix-F, Bruker Optik GmBH, Ettlingen, Germany) was not calibrated for cane samples that were stored for more than 72 hours after harvest, therefore only readings which were within calibration range were recorded. DAC analysis was then performed to further confirm results and to generate the complete dataset.

Data Analysis

For all the microbial and physiological assays a general analysis of variance (ANOVA) was performed. A mean separation post hoc test was performed, *viz.* Duncan multi range test (Duncan, 1955), to determine if means were significantly different.

Linear regression analysis was performed for all the industrial quality parameters measured in the different stalk portions. This was done to note which parameters showed a negative (decreasing) trend over time. Parameters which showed a negative trend, with $P \leq 0.05$, were noted. The results from the analyses described in this chapter are presented in the next chapter.

4. RESULTS AND DISCUSSION

4.1 Commercial Cane Quality and the Detection of Deterioration in Daily Cane Deliveries

The results of the control chart analyses for each ward and the statistical analyses for each grower are presented in this section.

4.1.1 Exploratory analysis of quality losses in the supply chain

Figures 4.1 and 4.2 present quality control charts (QCCs) for the Nkwalini ward. The *Pol % Fibre* and *RV % Cane* averages for each day from 2004 to 2009 were plotted. The Figures show that Monday exhibited average *Pol % Fibre* and *RV % Cane* values below the lower control limit. The QCCs for *Pol % Fibre* for all other wards (*cf.* Appendices 4-13) were created with the same design parameters, and the majority displayed a similar trend. From these results it is evident that Monday's quality was inferior to the rest of the week, represented by assignable cause variation as plotted on the QCC. This is evidence of system inefficiency and a resultant higher degree of quality loss over weekends. This inefficiency is further signalled by the fact that the assignable variation (below the lower control limit (LCL)) was repeatedly observed on specific days of the week (Monday and Tuesday) with significance levels at $P<0.01$.

Table 4.1 summarises the results of the QCCs for all the parameters analysed within all wards that indicated out-of-control processes. It identifies the days on which the parameter means were beyond the control limits. For example in Fig 4.1 it is evident that on Monday, *Pol % Fibre* was low in Nkwalini, this is denoted by "Mo^{L}" in Table 4.1.

From first principles *Pol % Fibre* can be considered to be a more reliable indicator of deterioration compared to *RV % Cane*. This is because after harvest fibre will not change as rapidly as cane mass. *Purity* also often indicated inferior quality on Mondays (Table 4.1), however, for this indicator both *Pol* (the numerator) and *Brix* (the denominator) change rapidly after harvest and both the numerator and the denominator represent substrates for the common microbial agents of postharvest deterioration (Eggleston *et al.*, 2004; Watt and Cramer, 2009; Saxena *et al.,* 2010). *Nonpol % Cane* and *Fibre % Cane*

may also not be considered reliable indicators because the denominator (cane mass) changes quickly after harvest as a result of various processes (Lyne and Meyer, 2005; Petit *et al.*, 2009; Watt and Cramer, 2009) and may result in an artificial increase after harvest in these indicators.

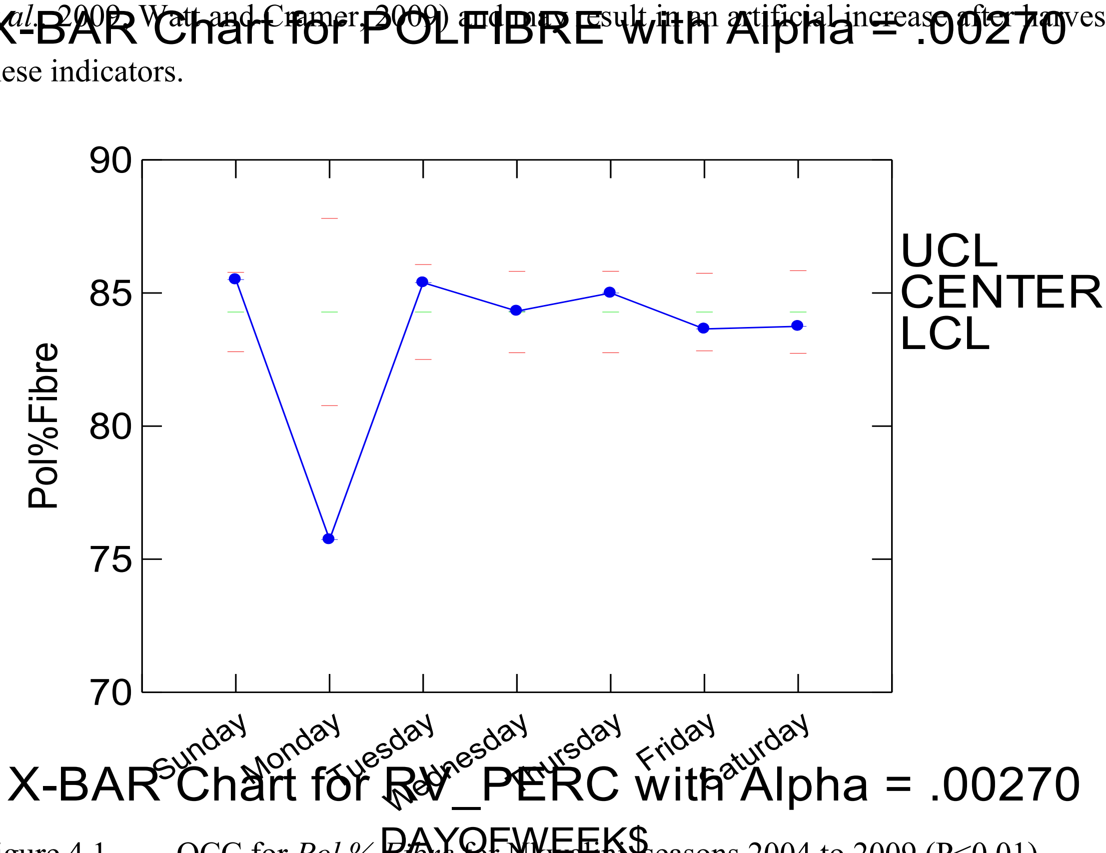


Figure 4.1 QCC for *Pol % Fibre* for Nkwalini, seasons 2004 to 2009 (P<0.01).

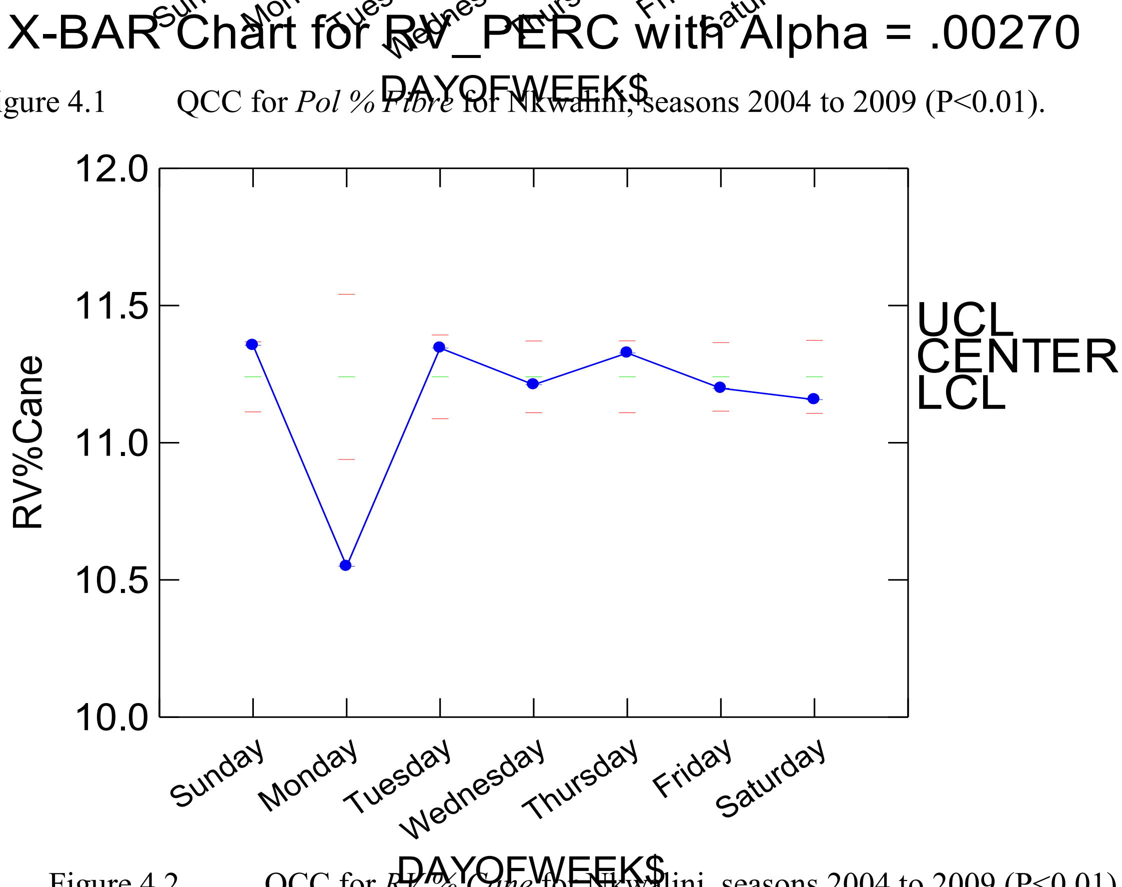


Figure 4.2 QCC for *RV % Cane* for Nkwalini, seasons 2004 to 2009 (P<0.01).

The QCCs also showed that a more severe reduction of *Pol % Fibre* in the early part of the week was noted in the summer months compared to the winter months. For example, in Figure 4.3 a reduction in *Pol % Fibre* was noted in November-December (2004-2009), but not during July-August (2004-2009).

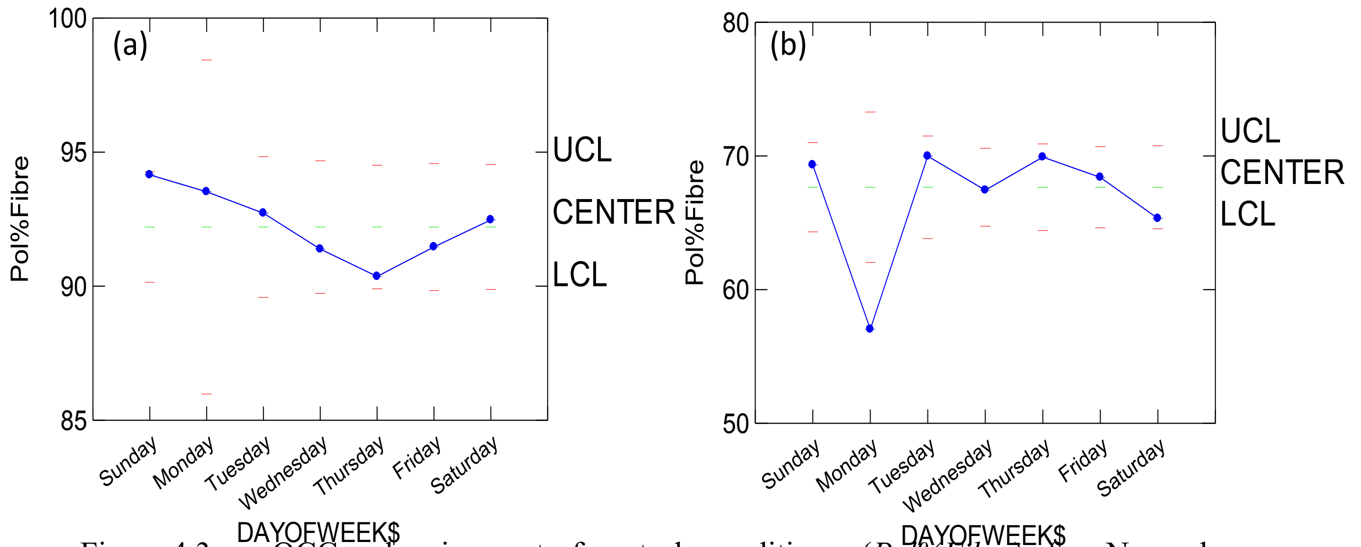


Figure 4.3 QCCs showing out-of-control conditions (*Pol%Fibre*) for November-December (b) compared to July-August (a) in Nkwalini (2004-2009) (P<0.01).

Table 4.1 Days of the week when cane quality parameters of the selected data in the Felixton mill supply area were outside the control limits (2004-2009).

Ward	*Fibre % Cane*	*Purity*	*Pol % Cane*	*RV % Cane*	*Nonpol % Cane*	*Pol % Fibre*
Empangeni central	Mo^{U} Tu^{U} Fr^{L}	Mo^{L} Tu^{L}	Tu^{L} Sa^{U}	Sa^{U} Mo^{L} Tu^{L}	Tu^{U}	Mo^{L} Tu^{L} Fr^{U}
Empangeni east	Mo^{U}	Mo^{L}			Mo^{U} Tu^{U}	Mo^{L}
Empangeni west		Su^{U} Tu^{L}			Tu^{U}	
Felixton flats	Su^{U} Mo^{U} Sa^{L}	Mo^{L} Tu^{L}	Mo^{L}	Mo^{L}	Mo^{U} Tu^{U}	Mo^{L} Sa^{U}
Felixton hills	Mo^{U}	Mo^{L}	Mo^{L}	Mo^{L}	Mo^{U} Tu^{U} Th^{L}	Mo^{L} Sa^{U}
Heatonville riparian	Mo^{U}	Mo^{L}			Su^{L} Mo^{U}	Mo^{L}
Heatonville scheme	Su^{U} Mo^{U} Sa^{L}	Mo^{L} Tu^{L} Th^{U} Fr^{U}	Mo^{L} Th^{U}	Mo^{L} Th^{U}	Tu^{U} Fr^{L}	Su^{L} Mo^{L} Th^{U}
Mposa			Su^{U}	Su^{U}	Tu^{U}	
Mtunzini	Sa^{L} Su^{U}		Mo^{L}			Su^{L} Sa^{U}
Nkwalini	Mo^{U}	Su^{U} Mo^{L}	Mo^{L}	Mo^{L}	Su^{L} Mo^{U}	Mo^{L}
Northern areas	Su^{L} Fr^{U}	Mo^{L}	Tu^{U} Fr^{L}	Mo^{L}Fr^{L}	Mo^{U}	Su^{U} Tu^{U} Fr^{L}

^{U}Above the upper control limit (UCL), ^{L}Below the lower control limit (LCL). Mo (Monday), Tu (Tuesday), Th (Thursday), Fr (Friday), Sa (Saturday), Su (Sunday).

From Table 4.1, it is apparent that weekend and early-week deliveries tended to exhibit assignable cause variations (in particular below the LCL for *Pol % Fibre*). Out of 11 wards investigated, only three wards showed a different trend. Data from Empangeni West did not exhibit any low assignable cause variation for *Pol % Fibre*, although *Purity* was significantly lower on Monday, Mposa did not exhibit any low assignable cause variation for the parameters analysed and Northern areas exhibited significantly lower *Pol % Fibre* on Friday, with significantly lower *Purity* on Monday. This outcome may imply that in Mposa logistical operations for delivering cane are exposed to only random variation, while in Empangeni West and Northern areas *Purity* is a more sensitive indicator of inefficiency in deliveries. Northern areas also shows a significantly lower *Pol % Fibre* on Friday. All the trends noted here and the assignable cause variations, may serve as a signals for the cane quality manager, indicating further investigation of the process is required and hence quality control charts are referred to as Phase I tools of process control (Montgomery, 2009).

The results, therefore, show that CTS data has substantial potential for monitoring supply chain processes in the sugar industry. *Pol % Fibre* deviations point to anomalies in upstream processes in the supply chain (from the field to the mill). Table 4.1 can be used as a basis to investigate out-of-control conditions, whether the parameters plot above or below the control limits.

As an indicator, *Pol % Fibre* appeared to be sensitive to out-of-control conditions (assignable cause variations) and due to the properties of this parameter, fewer false signals could be expected. An indicator, such as *Nonpol % Cane*, on the other hand, also seemed to identify out-of-control conditions, but due to the inherent complexity of this parameter (how the parameter is calculated), the results may be considered more random and unreliable.

From Table 4.1 and Figures 4.1- 4.2 (and 4.3 (b)) it is of interest that the days with undesirable quality averages are mostly from Sunday to Tuesday, which is an indication that there may be a problem in the supply chain over the weekend. These deviations cannot be attributed to inherent properties of the field or crop and suggests anomalies as a result of management practices.

The results in Table 4.1 and Figures 4.1- 4.2 represent a potential exploratory method for identifying quality problems in the supply chain at a ward-level. It is, however, important to be able to also assess grower performance with regards to cane deterioration. In the next section the results from individual grower data are presented.

4.1.2 Grower performance assessment

Figure 4.4 presents the average Δ*Pol % Fibre* values for each year corresponding to the grower's percentage of Significantly Deviated Weeks (SDW %) for that year. In comparing the SDW % and Δ*Pol % Fibre* a quality performance indicator (in terms of quality consistency) was generated in Figure 4.4. Only growers who delivered cane from 2004 to 2009 (six years) were plotted. Growers were sub-divided into four quadrants. The average Δ*Pol % Fibre* over the six years was 12.01 and the average SDW % was 21.07, these values were used to delineate the quadrants on the y and x-axes, respectively. In Figure 4.4, the data points in Quadrant four represents the worst performing growers (for a specific year), because they have both high SDW % and high Δ*Pol % Fibre* indicators. For

example in 2007 Grower 6, a poor performing grower in Quadrant four, had a SDW % of 28.57 and in these anomalous weeks the grower's average Δ*Pol % Fibre* was 25.08.

For the growers plotted in Figure 4.4, if a data point appeared in Quadrant 1 a weight of 1 was given, Quadrant 2 a weight of 2, Quadrant 3 a weight of 2 and Quadrant 4, weight 3. The sum of the weights for all six years (six data points) was calculated to give each grower a cumulative quality performance index for the six years, the higher the index the poorer the performance. Figure 4.5 shows the growers in descending order according to this index. The quality performance index (Figure 4.5) enables a ranking of growers with regards to delivery of cane which had significantly different quality in the first part of the week (Sunday –Tuesday) compared to the second half of the week (Wednesday-Saturday). For instance Figure 4.5 shows that grower 50 delivered sugarcane of relatively consistent quality throughout the week (low SDW % and low Δ*Pol % Fibre*), whereas grower 6 delivered cane with significantly differing quality in the first half of the week compared to the second half of the week (high SDW % and high Δ*Pol % Fibre*). All the data represented by these graphs (Figures 4.4 and 4.5) are significant at $P \leq 0.05$. Figure 4.4 shows that these indices can be used to monitor grower performance with regards to quality consistency at a seasonal level, whereas the method represented in Figure 4.5 illustrates the potential for multi-season analysis of grower performance based on cane quality.

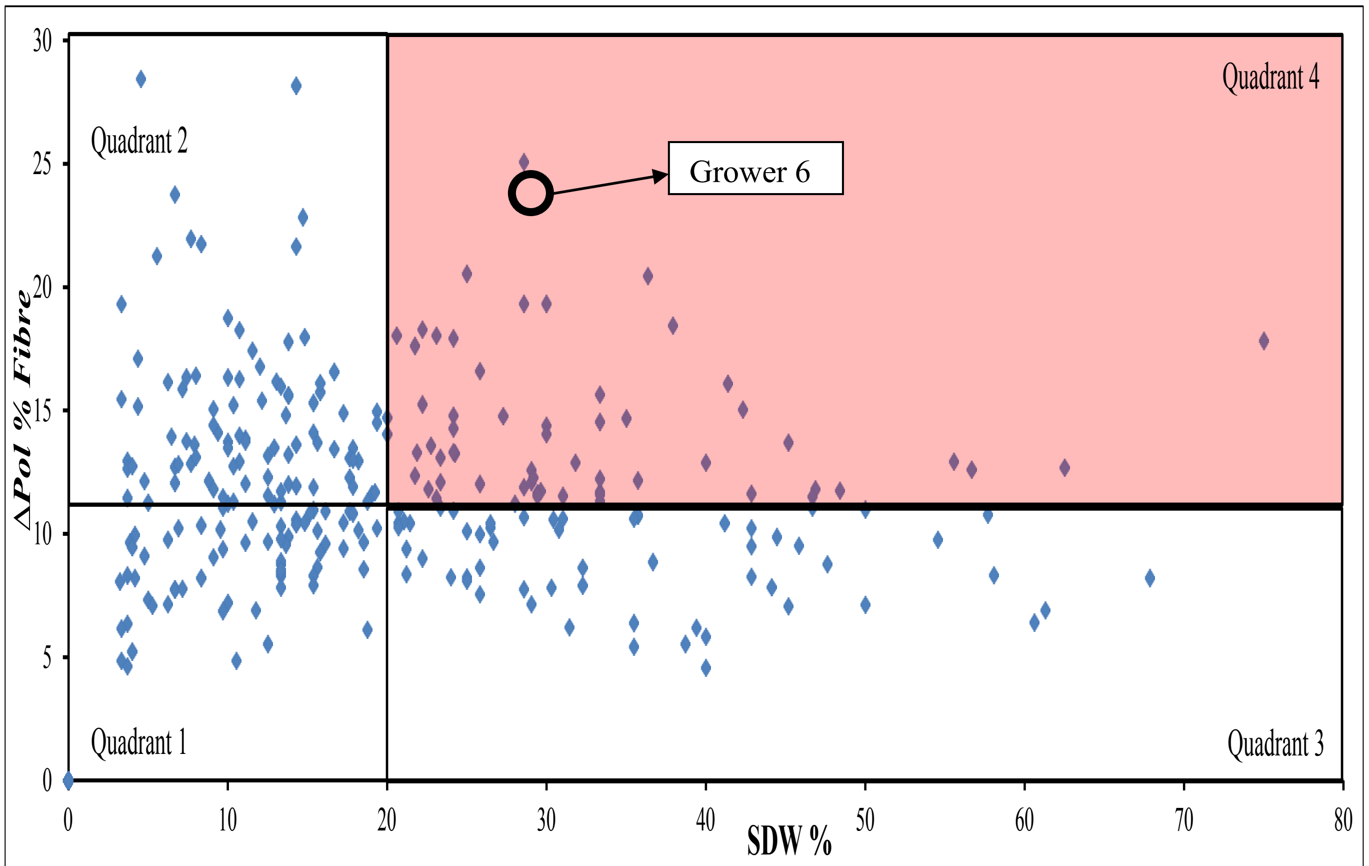


Figure 4.4 Distribution of growers according to SDW % and Δ*Pol % Fibre*. Growers in Quadrant 4 are poor performers with both high SDW% and high Δ*Pol % Fibre* indicators.

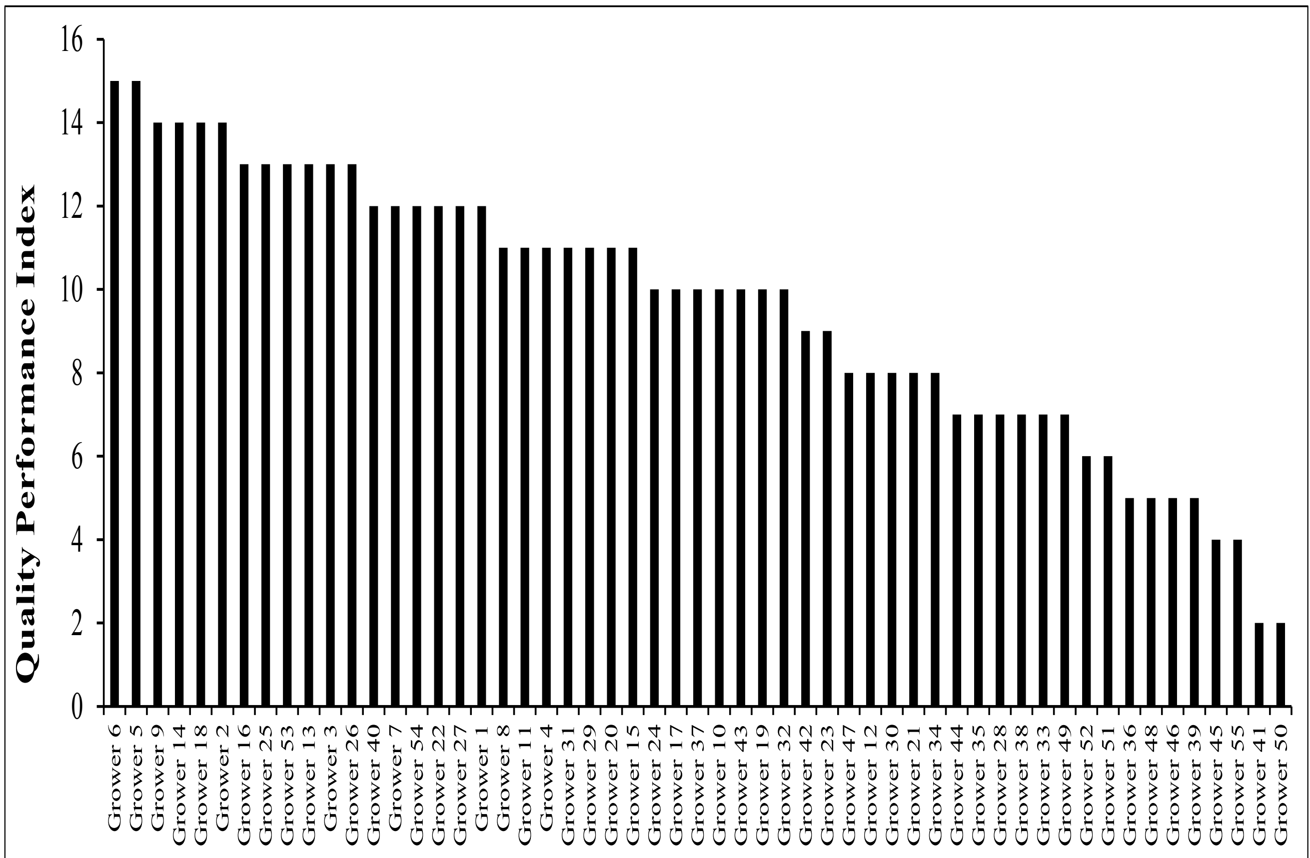


Figure 4.5 Growers in Felixton, ranked according to their performance in delivering consistent quality cane throughout the week. The index shows that the best performing grower from 2004-2009 was grower 50.

Pol % Fibre, based on the results in this section, shows potential as an indicator of BHTCD and deterioration. This indicator, together with other quality parameters and indicators of deterioration were further explored in this study at a smaller scale in two cane storage trials. In the next section the environmental conditions during the storage trials are presented.

4.2 Environmental Conditions during Storage

The values for air temperature and relative humidity are presented in Figure 4.6 and 4.7.

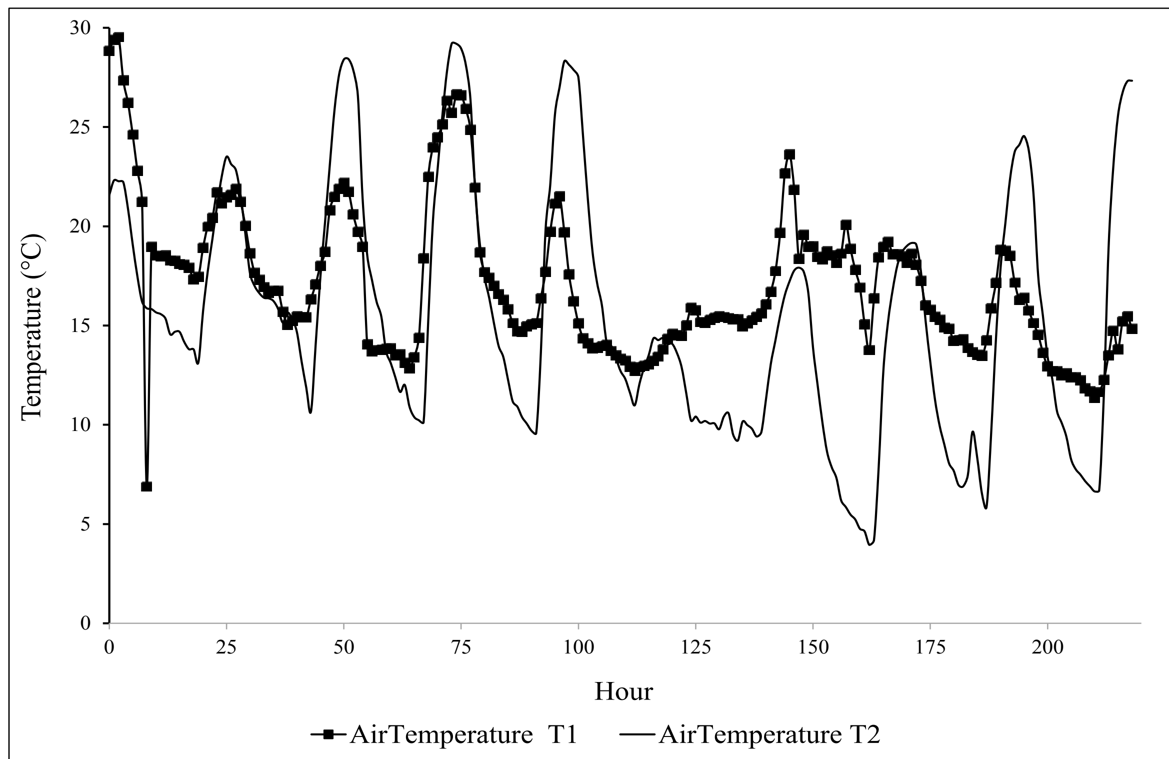


Figure 4.6 Hourly air temperature during the storage periods in both trials (T1 and T2).

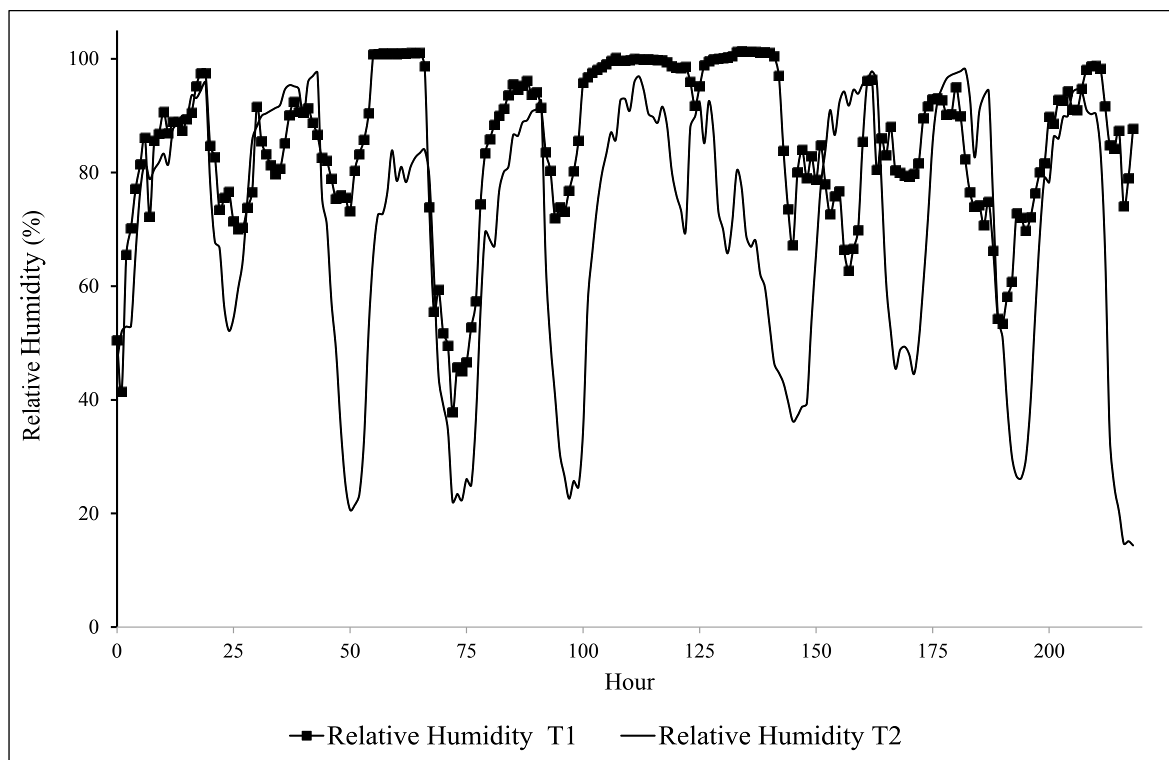


Figure 4.7 Relative humidity over 9 days in Trial 1 and Trial 2.

A summary of selected environmental attributes are presented in Table 4.2. Thermal time for the entire storage period was calculated as the cumulative value for temperatures above 10°C (TT1) for both trials (Ramburan, 2011). According to Garrity (2001) the *Leuconostoc* genus show optimum growth between 20°C - 30°C, and hence a second thermal time value (TT2) was calculated for all temperatures above 20°C during each storage period. It is acknowledged that thermal time is mainly used when assessing plant growth, but in this case it was solely used for the purpose of further describing environmental conditions during the storage periods as well in an attempt to portray the likelihood of microbial proliferation (TT2) during storage. The author was not able to find literature on the use of thermal time in the context of postharvest sugarcane deterioration studies.

Table 4.2 Selected environmental derivatives during the storage periods.

Trial	Average Air Temperature (°C)	Average VPD (kPa)	Rainfall (mm)	TT1(°C. hr)	TT2(°C. hr)
1	19.34	0.36	80.27	3738.93	949.57
2	19.90	0.72	6.60	3086.97	1222.45

*TT1 was calculated for all temperatures above 10°C, TT2 for temperatures above 20°C.

Table 4.2 indicates that the major difference between Trial 1 and Trial 2, with regards to the environmental conditions, was the higher vapour pressure deficit (VPD) in Trial 2, which means, overall, a lower relative humidity was experienced. TT2, however, shows that there were more incidences of temperatures above 20°C during Trial 2.

4.3 Microbial and Respiratory Activity

The results of the total bacterial colony counts, D-Lactate production and respiration rates are presented in the next sections.

4.3.1 Total heterotrophic bacteria colony counts

Table 4.3 shows the means of the total bacterial colony counts for each section from each trial (Variety×Section×Trial). It should be noted that, apart from contaminated plates, in general, fungal growth and yeast colonies were not detected and examples of the cell

pictures are illustrated in Appendix 1. A Duncan multiple range test (Duncan, 1955) shows that, overall, the population estimates were greater in Trial 1 and the cut-ends in general had greater counts than the middle sections. The Duncan test was performed as an ANOVA posthoc test and showed whether means deviate with statistical significance. Means were labelled with letters and those with different letters, such as the bottom and top sections of N12 in the Trial 1, are statistically significantly different at a P-value < 0.05. In addition Table 4.3 also displayed the results of the ANOVA, indicating significant, and non-significant, factors and interactions. The data in Table 4.3 are the means for the entire storage period.

Table 4.3 Means of estimated bacteria total heterotrophic bacteria colony counts (Log_{10} cfu g^{-1} FW) during the storage periods.

Variety	Sample	Trial 1	Trial 2
N12	Bottom	5.242^{fg}	4.928^{d}
N12	Middle	5.002^{de}	4.571^{b}
N12	Top	5.557^{h}	5.094^{ef}
N31	Bottom	5.306^{g}	5.117^{ef}
N31	Middle	4.743^{c}	2.783^{a}
N31	Top	5.829^{i}	4.908^{d}
L.S.D. at 5%	0.1582		
Variety	**		
Section	**		
Day	**		
Trial	**		
Variety×Section	**		
Variety×Day	**		
Variety×Trial	**		
Section×Day	**		
Section×Trial	**		
Day×Trial	**		
Variety×Section×Day	**		
Variety×Section×Trial	**		
Variety×Day×Trial	**		
Section×Day×Trial	**		
Variety×Section×Day×Trial	**		

**Significant at P<0.001

This study indicated that bacterial proliferation was significantly different between the two varieties (higher in N12), among sections, the storage periods and the trials ($P < 0.001$). The high bacterial counts at the bottom may be a result of soil splashing on the stalks prior to harvest. Eggleston *et al.* (2014) reported that *Leuconostoc* bacteria were associated predominantly with senescing brown leaves near the bottom of the stalk. Examples of colonies, the enumeration equipment and Gram-staining results are presented in Appendices 1-2. No attempt was made to identify specific dominant microorganisms. The

aim of this experiment, in the context of this project, was solely to monitor changes in total population estimates over time, similar to the work by Yusof *et al*. (2000) and hence identification was not performed. Figure 4.8 shows the interaction between Variety×Section×Day for each trial, on the total bacteria counts recorded. The effect of this three-way interaction is further discussed in section 4.3.4.

4.3.2 Lactic acid content

Table 4.4 shows the means of D-Lactate content in the cane portions in Trials 1 and 2 (Variety×Section×Trial). Trial 2 displayed higher values for D-Lactic acid. In both trials the bottom cut-end, which has more sucrose, appears to contain more D-Lactic acid. It is important to note that D-Lactic acid production is a result of bacterial metabolism during the fermentation of sugars, in particular glucose and fructose, which are also substrates for plant respiratory activity (Eggleston *et al.,* 2004; Mao *et al.,* 2006; Watt and Cramer, 2009). Therefore, this might be the reason why, even though Trial 2 had lower total counts of bacteria, there was an increased lactic acid production due to the decrease in plant respiration, as noted by the decrease in respiration rate (Table 4.5).

Table 4.4 Means of D-Lactate ($g100g^{-1}FW$) during the storage periods.

Variety	Sample	Trial 1	Trial 2
N12	Bottom	0.0753^{ab}	0.6088^{d}
N12	Middle	0^{a}	0.2563^{abc}
N12	Top	0.0483^{ab}	0.2990^{bc}
N31	Bottom	0.0387^{ab}	0.9836^{e}
N31	Middle	0^{a}	0.2990^{bc}
N31	Top	0.0322^{ab}	0.4486^{cd}
L.S.D. at 5%	0.2496		
Variety	NS		
Section	**		
Day	*		
Trial	**		
Section×Trial	**		
Day×Trial	**		
Variety×Section	NS		
Variety×Day	NS		
Variety×Trial	NS		
Variety×Section×Day	NS		
Variety×Section×Trial	NS		
Variety×Day×Trial	NS		
Section×Day×Trial	*		
Variety×Section×Day×Trial	NS		

*: Significant at P<0.05; ** Significant at P<0.001; NS Not Significant

Table 4.4 shows significant variation was a function of the different sections, the storage period and the trials. The three-way interaction of Section×Day×Trial showed that in Trial 1 the cut-ends (bottom and top) gradually experience an increase in lactic acid content after day 7. In Trial 2, however, the cut-ends (specifically the bottom) experienced a decrease in lactic acid content during the storage period. In these experiments, variety alone could not be proven to be a contributor to the variation observed in D-Lactate production, even though in bacterial proliferation (Table 4.3) variation was significantly influenced by variety.

Figure 4.10, in section 4.3.4, shows the trends observed in the interaction between Variety×Section×Day, for each trial, in D-Lactic acid production and the effect of this interaction is discussed .

4.3.3 Respiration rate

The average respiration rates in the different stalk portions for both Trial 1 and Trial 2 are presented in Table 4.5 (Variety×Section×Trial). The means were further described using the Duncan Multiple Range Test (Duncan, 1955). From Table 4.5, it is apparent that there was a lower respiration rate in Trial 2. This lower respiration rate was accompanied by higher means of lactic acid produced (Table 4.4), this might be due to an increase in the microbial breakdown of sugars (microbial respiration) in Trial 2. It is of interest that there was an absence of a notable change, between trials, in the respiration rate of the middle portions of the cane. The most significant change in respiration rate between Trial 1 and 2 was observed in the top portions. This is consistent with the data by Rizk and Normand (1969), which illustrated that the most significant change in cane enzymatic activity occurs in the top portion after burning cane. The author also noted a lack of recent literature on postharvest changes in the different sections of cane stalks. This may potentially present opportunities for further studies on the behaviour of different parts of cane stalks during delays after harvest.

Table 4.5 Means of respiration rates (CO_2 mL kg^{-1}FW hr^{-1}) during the storage periods.

Variety	Section	Trial 1	Trial 2
N12	Bottom	3021^{c}	1907^{ab}
N12	Middle	2204^{abc}	2500^{bc}
N12	Top	6120^{d}	1401^{a}
N31	Bottom	2948^{c}	1438^{a}
N31	Middle	1641^{ab}	2261^{abc}
N31	Top	5725^{d}	1783^{ab}
L.S.D. at 5%	790.1		
Variety	NS		
Section	**		
Day	NS		
Trial	**		
Variety×Section	NS		
Variety×Day	*		
Variety×Trial	NS		
Section×Day	NS		
Section×Trial	**		
Day×Trial	**		
Variety×Section×Day	*		
Variety×Section×Trial	NS		
Variety×Day×Trial	*		
Section×Day×Trial	NS		
Variety×Section×Day×Trial	*		

*Significant at P<0.05, **Significant at P<0.001, NS Not Significant

Table 4.5 suggests that, similar to D-Lactic acid production (Table 4.4), variety alone was not proven a contributor to the variation in respiration rates over the storage periods. However, the respiration rates in different days also were unable to show a contribution to variation. Respiration rate was effectively influenced by the cane sections and the trials. The three-way interaction Variety×Day×Trial, showed that during the storage period there was a higher respiration rate experienced by N12, specifically in Trial 1. In Trial 2, even though there was no significant difference in respiration rate between varieties during the

storage period, the respiration rate in N12 was higher than N31. This might be due to the higher bacteria proliferation in N12 (Table 4.2). N12 is also a higher sucrose variety compared to N31 (Anonymous, 2006) and hence may have had greater substrate availability for both plant and microbial respiration. For both varieties during the storage period in Trial 1, the top section respired the most and in Trial 2 the respiration rate was generally similar (slightly higher in the middle sections) along the stalk length (Variety×Section×Day×Trial). This might have been due to the high microbial infection and high plant respiration in the least mature top portions in Trial 1 and for Trial 2 the suppressed plant respiration may have resulted in less difference in respiration rate among stalk sections. Figure 4.9 (section 4.3.4) shows the effect of the interaction between Variety×Section×Day for each trial, on the respiration rate observed.

These results show that the primary factors influencing the production of CO_2 (in respiration) and D-Lactate were the stalk sections as well as the trials, with variety only playing a significant role when combined with these other factors. However, it should be acknowledged that there are other products of bacterial degradation, which, if measured, might reflect the influence of varieties in postharvest deterioration. The measurement of these products, such as dextran, ethanol and mannitol (Eggleston *et al*., 2008; Walford and Nel, 2010), was not performed due to time and budget constraints.

4.3.4 Analysis of total counts, respiration and D-Lactic acid over time

The trends in three parameters were plotted over the storage duration in Trial 1 and 2. These parameters *viz.* total heterotrophic bacteria counts, respiration rate and D-lactate production are presented in Figures 4.8 - 4.10, respectively.

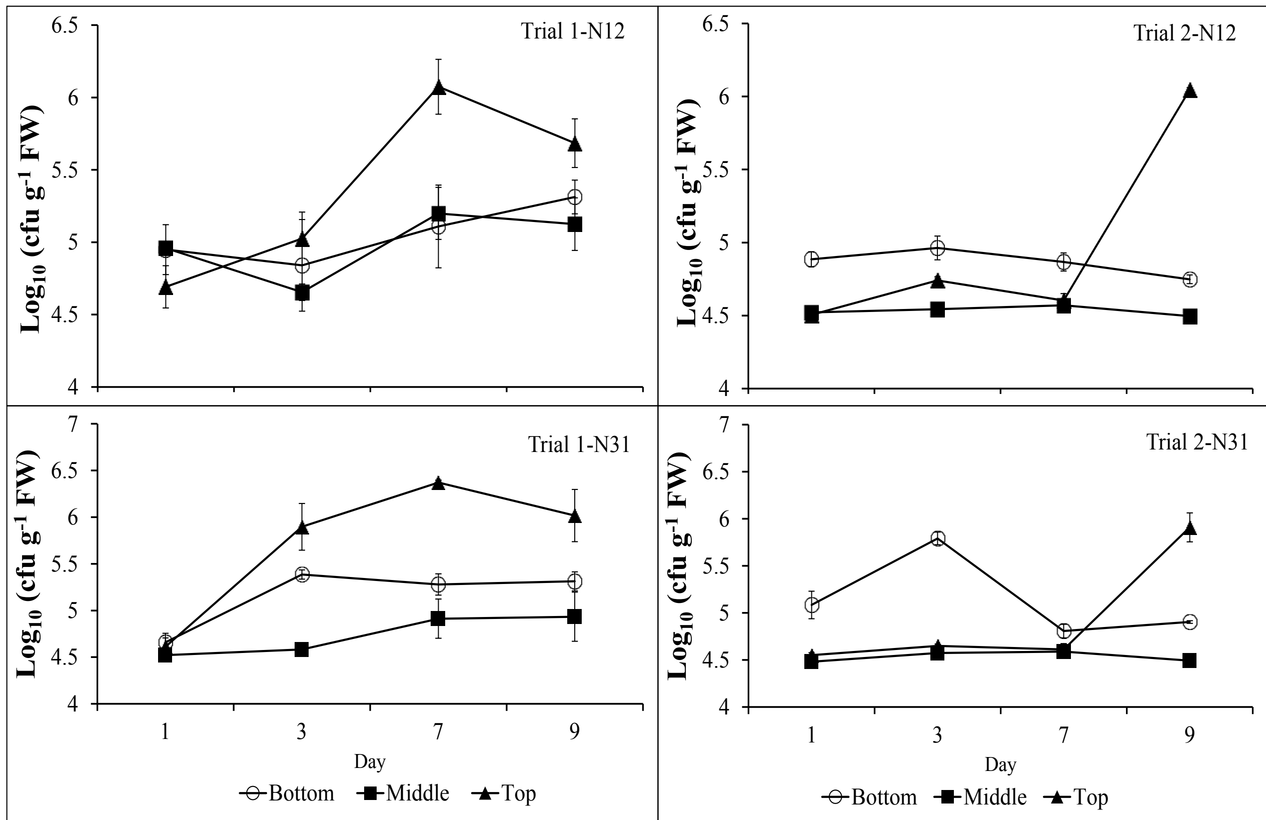


Figure 4.8 Total count trends during the storage period in Trial 1 and Trial 2.

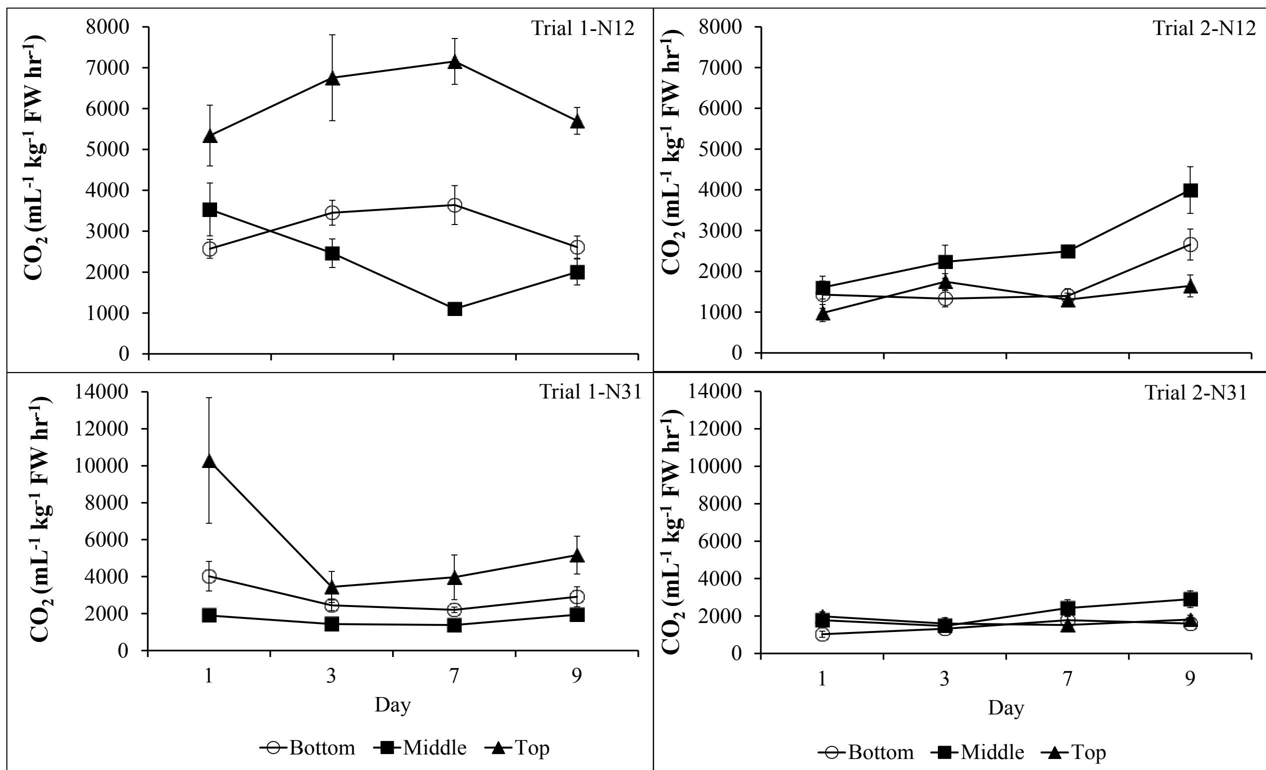


Figure 4.9 Respiration rate trends for the different stalk portions in Trial 1 and Trial 2.

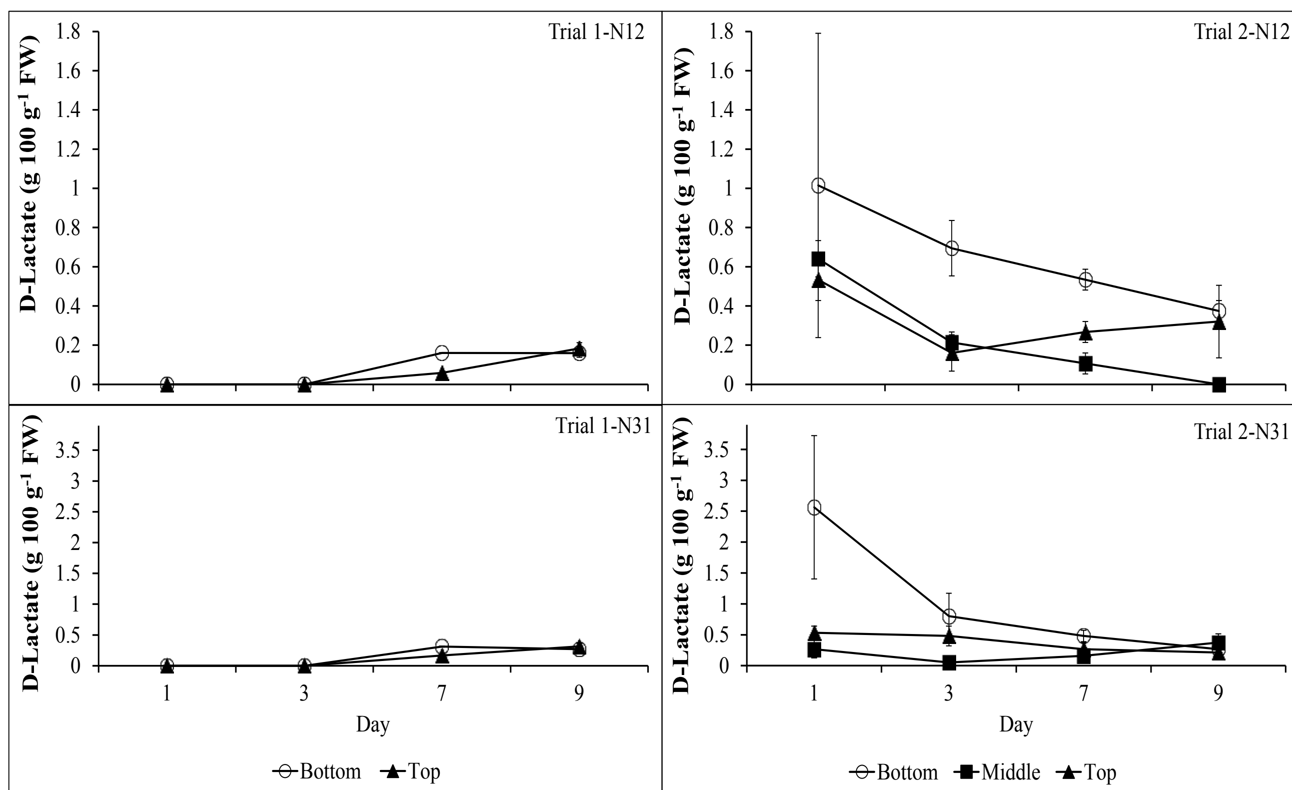


Figure 4.10 D-Lactate production during the storage time in Trial 1 and Trial 2.

The reduced respiratory activity in Trial 2, as observed in Figure 4.9 may primarily have been due to reduced cane enzymatic activity as a result of burning (Dymond, 1924; Rizk and Normand, 1969). Figure 4.10 shows that D-Lactate production was not significantly ($P \leq 0.05$) different between N12 and N31 over time.

Although thermal time two (TT2) was higher in Trial 2, the relative humidity (RH) was appreciably lower than in Trial 1. Lower microbial proliferation in Trial 2 may therefore have been a result of the lower RH. Solomon *et al.* (2006) and Uppal *et al.* (2000) also report that a combination of high temperature and humidity leads to an increased probability of microbial proliferation in harvested cane.

As mentioned before, a negative correlation trend was noted between respiratory activity and D-Lactic acid. In Figure 4.9 and 4.10, it is evident that the respiration rate generally decreased over time in Trial 1 and increased in Trial 2, whereas D-Lactic acid increased in Trial 1 and decreased in Trial 2. It should however be noted that due to the variation in mechanisms of deterioration by *Leuconostoc* bacteria (Walford and Nel, 2010), it is

possible that other metabolites such as mannitol (Eggleston *et al.*, 2008) or products such as dextran (Walford and Nel, 2010) may have been more sensitive markers of deterioration in Trial 1 (day 1 to 5). The high standard error for the bottom section on day 1 in Trial 2 also calls into question the suitability of this metabolite for indicating deterioration in cane. Day 3 to day 9, in Trial 2, show a decline in D-Lactic acid which may further point to the probability of other products of microbial deterioration, because microbial counts were still high on day 3 in Trial 2. The limitation of selecting one bacterial metabolite in such a study is therefore acknowledged. Due to the varying bacterial pathways of deterioration (Walford and Nel, 2010), it is recommended for future studies to monitor as wide an array of bacterial deterioration products as possible (taking into consideration any practical constraints).

From the results presented in this study, it is evident that sugarcane deterioration after harvest involves interactions between microbial activity, as well as the plant respiration. This is found to be in agreement with Watt and Cramer (2009). It should also be noted that the impact of burning on the suppression of cane enzymic activity and the resultant degradation of carbohydrate reserves after harvest depends on the intensity of the fire (Rizk and Normand, 1969). Burning of cane may also introduce more infection sites for microorganisms (Solomon, 2009), however, the bottom and top cut-ends still present the easiest access areas for infection.

It should be noted that these experiments were performed under relatively low temperatures compared to conditions that have been previously reported to influence deterioration (such as in Solomon, 2009). In Trial 2 low relative humidity conditions were also experienced. From the literature (such as Bandhari and Singh, 1986; Eggleston *et al.* 2008; Solomon, 2009) it can be inferred that any trends observed here would be intensified under high ambient temperatures and high humidity.

These results suggest that, under low temperature storage conditions, burning cane and the resultant effect it has on the cane's enzymatic activity may retard the detrimental effect of reserve sugar breakdown through plant respiration. However, the significantly ($P \leq 0.05$) higher D-Lactate values in the cut-ends of cane stalks in Trial 2 may indicate that in the

absence of cane-enzyme induced plant respiration, sucrose and reducing sugar breakdown proceeds increasingly via the microbial route.

The microbial and plant respiration in sugarcane after harvest ultimately has an important effect on the biochemical parameters of quality. The changes observed in the biochemical parameters are presented in the next section.

4.4 Mill Room Parameters

The analysis of cane samples from mill room parameters over time showed that consistent declining trends were detected in Trial 1. Furthermore, the only parameters to show significant declining trends in both varieties were *Brix % DM* and *Pol % Fibre*. These parameters, shown in Figures 4.11 – 4.12, displayed a decrease over time in the top cane portions for both varieties in Trial 1, the negative trend was shown to be significant at P≤0.05.

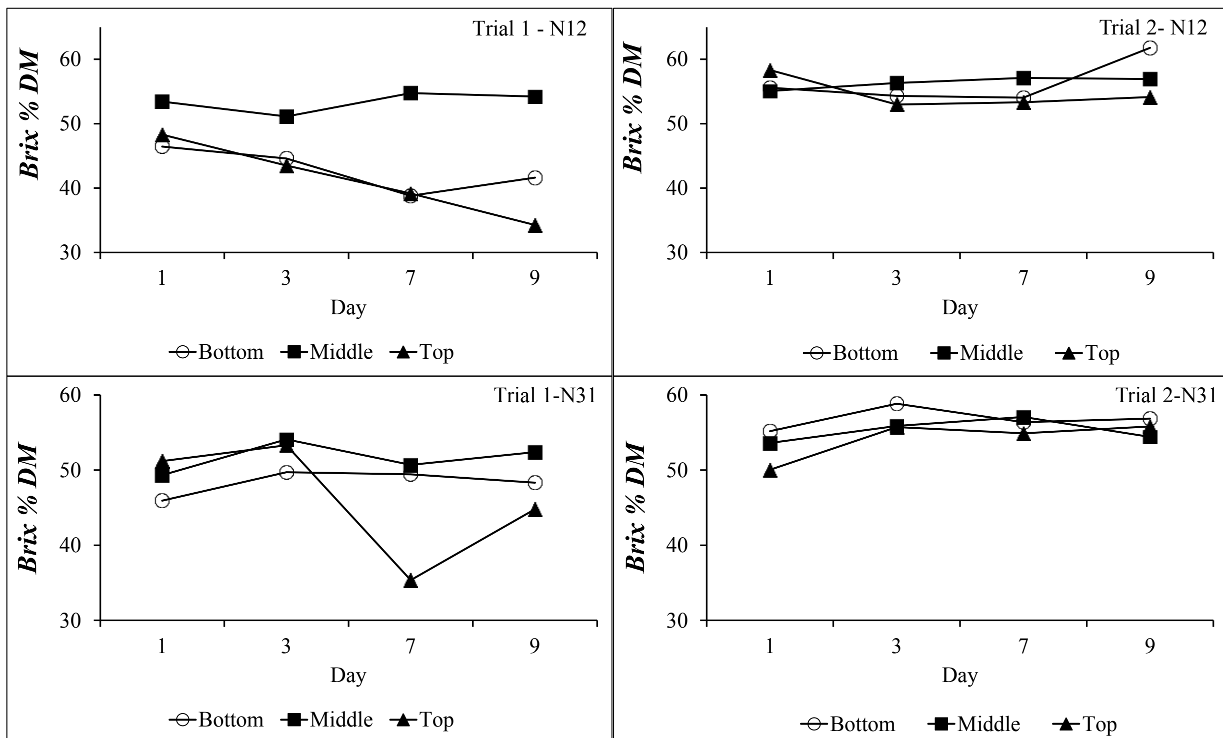


Figure 4.11 The change in *Brix % DM* over the 9-day storage period (P≤0.05).

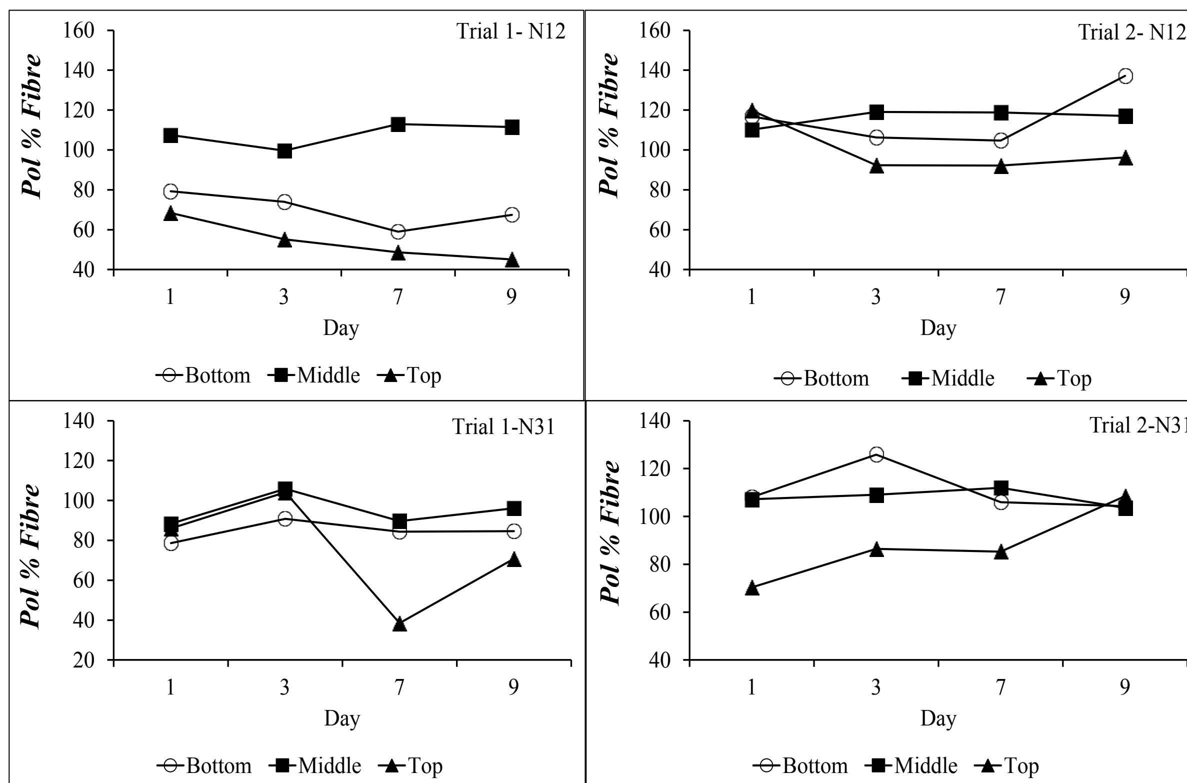


Figure 4.12 The change in *Pol % Fibre* over the 9-day storage period (P≤0.05).

From the results in Figures 4.11 - 4.12 it appears that the values for *Pol % Fibre* and *Brix % DM* were higher in Trial 2 compared to Trial 1. Figure 4.12 shows that during the storage period in Trial 2 *Pol % Fibre* in the different stalk portions did not change significantly (P≤0.05). Rizk and Normand (1969) also found that variations in the changes of quality parameters in different stalk portions (and varieties) during storage were, generally, less pronounced in burnt cane as opposed to unburnt cane. It should be noted that in these experiments the lowest *pol* and °Brix values were found in the top portion of cane stalks. The literature (such as Rizk and Normand, 1969; Alexander, 1973) also confirms that this portion has the highest enzymatic activity due to growth.

It is of interest that the effect of respiration (plant and microbial) after harvest can be noted in the decrease in *Pol % Fibre*. In Figures 4.13 and 4.14 the top sections of the cane, which showed higher CO_2 production in Trial 1 subsequently exhibited a declining trend of *Pol % Fibre*. In Trial 2 there was no significant difference in CO_2 production along the length of the stalk, and subsequently there was no declining trend noted for *Pol % Fibre* in any of the cane portions.

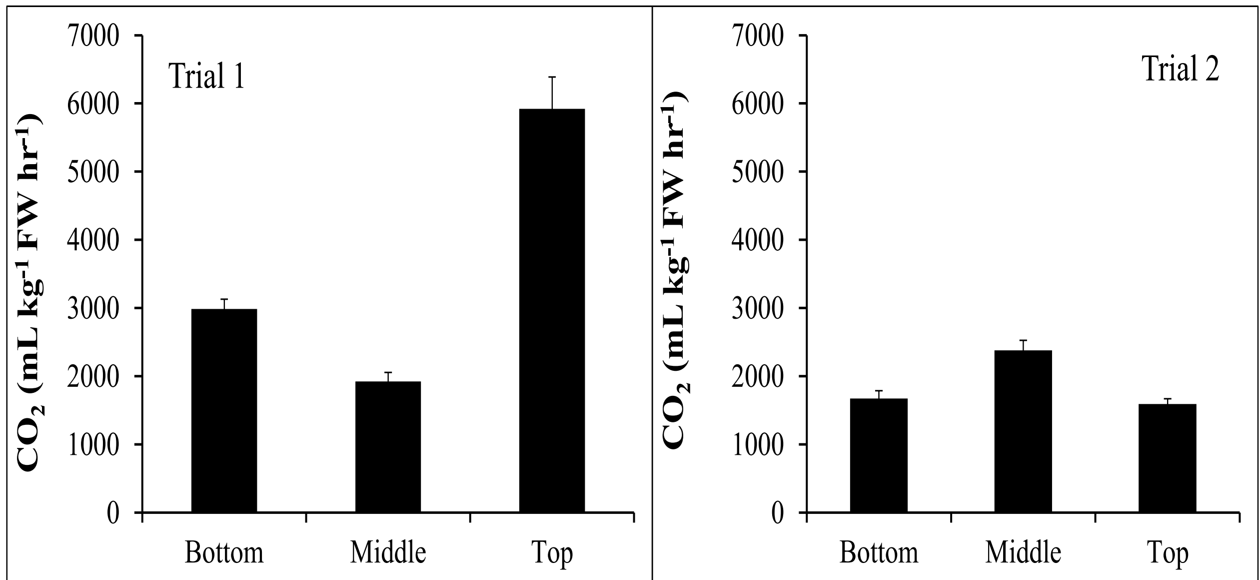


Figure 4.13 The respiration rate in Trial 1 and 2.

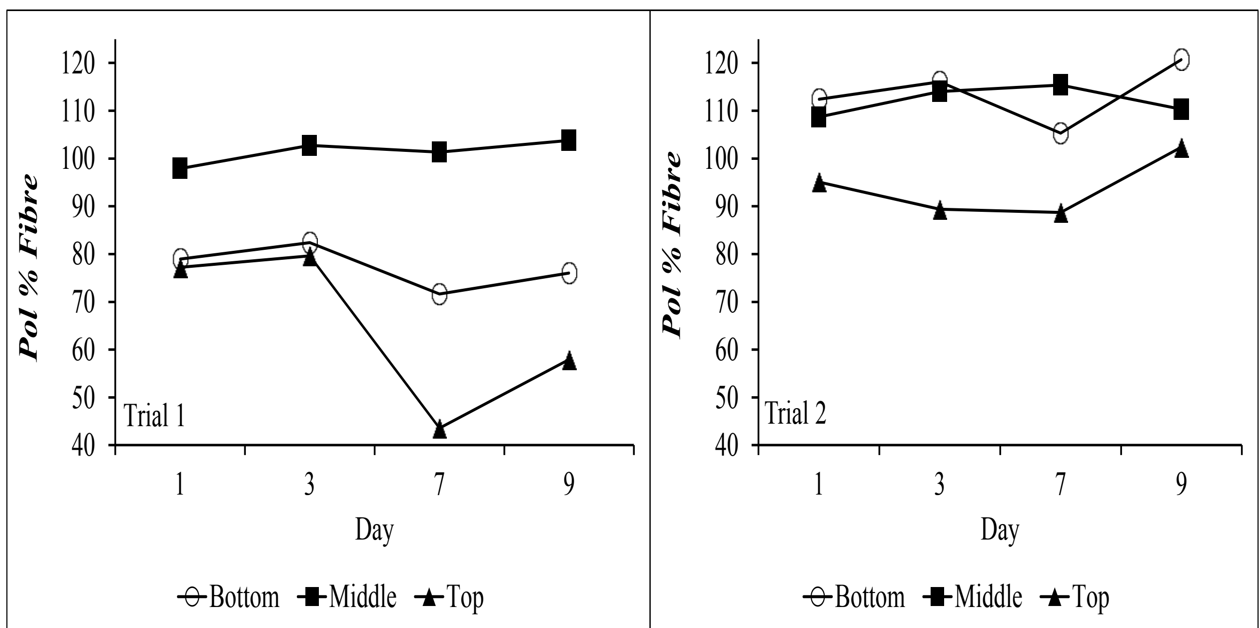


Figure 4.14 The change in *Pol % Fibre* during Trial 1 and 2, without considering variety.

The data from the SASRI mill room analyses indicated that the top (less mature) stalk portions showed the most change in quality parameters over the storage period and may deteriorate faster. It is acknowledged, however, that due to storage constraints uneven replication of samples may have been a limitation during the SASRI laboratory

experiments in Trial 2. Another limitation that must be acknowledged, due to freezer storage space constraints, was the lack of capacity to perform the described storage experiments for both burnt and unburnt cane at the same time. Due to the selected storage periods, it should be noted that there was no significant difference in ambient temperature during storage, with only higher humidity recorded in Trial 1 due to rainfall events. Controlled storage environments were not used because the aim was to simulate industry conditions. However, some conclusive results with regards to deterioration indicators were obtained from this study.

Overall, the data obtained during Trials 1 and 2 showed that changes in cane quality were most significant in the cut-ends. Trial 1 showed that the top (less mature) sections, which are more physiologically active according to the literature, showed the highest loss in *Pol % Fibre* during storage. This is in agreement with the findings of Fernandes and Benda (1985) who showed that, in unburnt cane, quality decreases rapidly near the top of the stalk. This further suggests that immature cane deteriorate faster after harvest. Furthermore, even though Trial 2 had higher D-Lactic acid, during the cool and dry storage period there was no significant decline in any of the mill room quality parameters. The significant reduction in plant respiration in Trial 2 might therefore be beneficial for maintaining quality during the storage period provided that temperatures are low.

In the next section, further discussion, an attempt to identify the key outcomes, recommendations for industry and future research are presented.

5. FURTHER DISCUSSION, CONCLUSIONS, RECOMMENDATIONS FOR INDUSTRY AND FUTURE RESEARCH

The South African sugarcane supply chain is plagued by fluctuating burn/harvest-to-crush-delays (BHTCDs) due to a variety of reasons, for example transportation inefficiency, difficulty in getting cane out of the field after heavy rainfall events and mill breakdowns. The delay in delivering sugarcane to the mill has an effect on cane quality, which eventually affects sugar extraction operations in the factory as well as sugar quality. However, the current cane payment formula, which focuses on recoverable value and relative recoverable value (Wynne, 2009), lacks an indicator which enables the estimation of deterioration after harvest. Certain growers have the misconception that allowing harvested cane to lie in the field for long periods increases their revenue (Lyne and Meyer, 2005). Sometimes the recoverable value (*RV % Cane*) may appear to increase during the period after harvest, which may be due to false increases in the measured *pol* as a result of dextran formation (Uppal, 2003; Naqvi *et al*., 2014).This delayed cane may therefore still present extraction challenges in the mill (Ravno and Purchase, 2005). Even with the knowledge of the mass loss, and hence the decrease in tons *RV*, some growers still opt to deliver delayed cane (Lyne and Meyer, 2005). This increase in *RV % cane* serves as a dis-incentive to growers to deliver cane to the mill promptly after harvest. This study attempted to develop an indicator which could signal the delivery of deteriorated cane consignments.

The comparison of postharvest technologies in the sugar and the fresh produce industries showed that fresh produce industries have more demanding quality requirements. However, it was noted that the sugar industry could benefit from the use of non-destructive quality measurement techniques such as NIRS, which can also be calibrated to measure the various chemical indicators of deterioration, such as ethanol and lactic acid. The application of anti-microbial solutions on cane stalks after harvest was also noted to be beneficial, and their value can also be noted in the experimental trials carried out in this study where the cut-ends experienced greater bacterial infection compared to the middle of the stalk.

The study carried out at the Felixton mill area confirms the value of *Pol % Fibre* as a potential indicator of deteriorated cane. The quality control chart technique demonstrated in this study enabled the identification of days of the week during which the quality of cane was of an undesirable standard. In the Felixton mill area the quality control charts were used as Phase I tools of statistical process control, and this implies that they only enabled the identification of an out-of-control process, in this case showing significant out-of-control processes in the first half of the week at $P<0.01$. This study, therefore, presented a statistical technique for quantitatively signalling poor cane quality deliveries in the supply chain. Further empirical investigations in the Felixton area might be required to conclusively determine the reason for the significant decline in *Pol % Fibre* in such a specific manner.

The outcome of the statistical analyses of CTS data enabled the identification of trends in poor quality deliveries. Extraction of such information from CTS data is proof that this data has the capacity to be used for the purposes of integrating the supply chain through quality improvement strategies and this represents a significant outcome of the study. The results of CTS data analysis may be used for frequent reviews of grower performance and serve as a basis for identifying and investigating significant reductions in quality. This is the first study that utilised the CTS database in this manner and shows it to be a useful resource for monitoring or analysing the sugarcane supply chain in South Africa. Furthermore, this study was the first to use Quality Control Charts (QCCs) as an exploratory technique in the South African sugarcane supply chain. The author was unable to find any literature on the application of this technique in other sugar industries. In Turkey, Sumnu (2000), showed the applicability of QCCs for monitoring quality of pears during storage and facilitating the maintenance of quality loss within acceptable limits. This technique has been shown, in manufacturing industries globally, to be valuable in monitoring the quality of products and signalling anomalies.

The environmental conditions during both trials might have influenced the results observed. The literature shows that cane quality after harvest was influenced under high ambient temperature and high relative humidity. During both trials low temperatures were experienced. Any trends or changes observed in this study may therefore be considered to be conservative and it is expected that more deterioration would be noticed under higher

ambient temperature conditions. This can also be noted from the results in the Felixton study (Figure 4.3) where a significant drop in *Pol % Fibre* was recorded for the summer months and not the winter months. It should also be noted that the results presented for the trials are for whole-stalk cane samples, deterioration behaviour of billeted cane is expected to be different.

The effect of microbial and plant respiration was noted primarily in the cut-ends of sugarcane during the storage periods. In Trial 1, the highest respiration and bacterial proliferation was in the top portion of each variety, while in Trial 2 the respiration rates did not significantly ($P \leq 0.05$) differ along the length of the stalks, whereas bacterial proliferation was highest in the bottom portion of the stalks. D-Lactate production was highest in the cut-ends in both trials, correlating to the portions of highest bacterial proliferation, D-Lactate production was also notably higher in Trial 2.

Overall, the microbial and plant respiratory activity of sugarcane after harvest impacts the carbohydrate quality parameter, *viz. pol* (an estimate of sucrose) which is required for the production of sugar in the factory. *Pol % Fibre* and *Brix % DM* were found to be the only parameters that showed a consistent declining trend at $P \leq 0.05$ in the top portions of both varieties. Of these 2 indicators, *viz. Pol % Fibre* and *Brix % DM*, *Pol % Fibre* presents the most reliable parameter, since the postharvest degradation of fibre is at a slower rate than the degradation of the other components of dry matter (which is the denominator of *Brix % DM*). In Trial 2 none of the parameters measured showed a declining trend.

From the results of the experimental storage trials and the Felixton mill area study, it was noted that *Pol % Fibre* may provide a reliable signal for cane quality deterioration. Furthermore, in the experimental BHTCDs *Pol % Fibre* showed a significant decline in the less mature top section of the cane. This is the first study to identify *Pol % Fibre* as a quality parameter and demonstrate its value for this purpose.

This study therefore contributed significantly to the body of knowledge under postharvest management of cane quality. With the application of a statistical quality control technique for the first time in a South African agro-industry (this is assumed based on a lack of publication in this area), CTS cane quality data was used for diagnosing potential cane

supply chain logistical challenges. This investigation also resulted in the development of a novel cane quality indicator that can be easily monitored within the supply chain context and used this indicator to develop a grower performance index based on cane quality data. These outcomes present valuable information for use by growers and professionals involved in cane quality and cane supply chain management in South Africa. The results of the two storage trials also provided valuable information with regards to the deterioration behaviour, along the stalk length, of cane during delays between harvesting and crushing.

In accordance with the significant changes observed in the top sections of the cane the literature also confirms that in the top section of unburnt cane the enzymatic activity resulting in the breakdown of sucrose after harvest is significantly higher than in the mature parts of the cane. This further strengthens the notion that immature cane may experience faster deterioration than mature cane after harvest. This has implications for the use of ripeners prior to harvest as well as harvesting techniques, for example determining topping height. These recommendations are presented in the next section.

5.1 Recommendations for Industry

The information from this study may be useful to growers, millers, researchers, extension officers and other practitioners in the sugar industry who are concerned with postharvest quality. It should be noted that quality after harvest is significantly affected by preharvest inputs and conditions (for example fertilizer, environment, ratoon). However, to maintain quality present after harvest it is advisable to:

- Consider *Pol % Fibre, RV % cane* and *Purity* as indicators that could be monitored at least bi-monthly for inferior quality deliveries as a result of assignable variation,

- at a seasonal level grower performance could be assessed using the SDW % and Δ*Pol % Fibre* indices (see Section 4.1.2)

- the results of the top sections in Trial 1 also indicate that the use of chemical ripeners to hasten maturity prior to harvest might be beneficial, the benefit of

chemical ripeners has also been reported by other researchers (for example Clowes and Wood, 1978; van Heerden, 2012),

- as has been published (for example Eggleston *et al.*, 2008; Solomon, 2009) and confirmed in this study, in humid conditions, more significant changes were noted in cane quality. It is, therefore, advisable to attempt to shorten the BHTCD as much as possible especially during summer months,

- in addition to shortening BHTCD in summer months it would be even better if the length of the milling season was reduced so as not to extend into the warm and humid months such as December, and

- the most activity was noted in the cut-ends which present easier access points for bacterial infection. Therefore the use of anti-bacterial solutions, such as benzoalkonium and glutaraldehyde sprays (Singh *et al*., 2008) as well as Sucroguard® (Kulkarni and Warne, 2004), which can be applied to cut-ends may facilitate the reduction of infection during the BHTCD.

In the next section, recommendations for future research avenues are presented.

5.2 Recommendations for Future Research

In light of the discussed outcomes future research should be carried out to:

1. Empirically investigate the interaction between physiological and microbial activities in mature versus immature cane, with a more detailed emphasis on the products of microbial degradation, and an attempt to determine the impact of these interactions on sucrose content (by monitoring sucrose) during the harvest-to-crush-delay. This would involve whole stalk sampling, and

2. performing experiments monitoring the above-mentioned parameters in hot and humid summer period over a typical BHTCD timeframe,

3. calibration of NIRS for the products of microbial degradation, to facilitate rapid identification and quantification of these products in tissue samples of both unburnt and burnt cane, as well as cane of varying maturity levels and postharvest delays, to be able to have a detailed measurement of the quality of cane consignments at-line as they arrive at the mill,

4. monitoring *Pol%Fibre* in mature (or ripened) versus immature cane over a selected BHTCD period,

5. determine values of *Pol % Fibre* which correlate to low sucrose recoveries in harvested stalks and hence develop a deterioration model, which can be calibrated for each season and used to signal deteriorated cane at shorter intervals, within the season.

This study showed that *Pol % Fibre* has potential to be used in the industry to monitor quality after harvest. Cane quality after harvest is often influenced by a number of factors, for example handling, harvesting technique, and transport, therefore quality management has the potential of integrating the supply chain through engagement of a number of stakeholders involved in these various operations. It should be acknowledged that postharvest losses in agricultural produce are inevitable and acceptable levels of losses should be identified according to commodity, season and production region to facilitate quality management (Kader, 2005). The use of appropriate statistical techniques as well as monitoring the correct quality parameter may serve as an invaluable addition to postharvest quality management of sugarcane.

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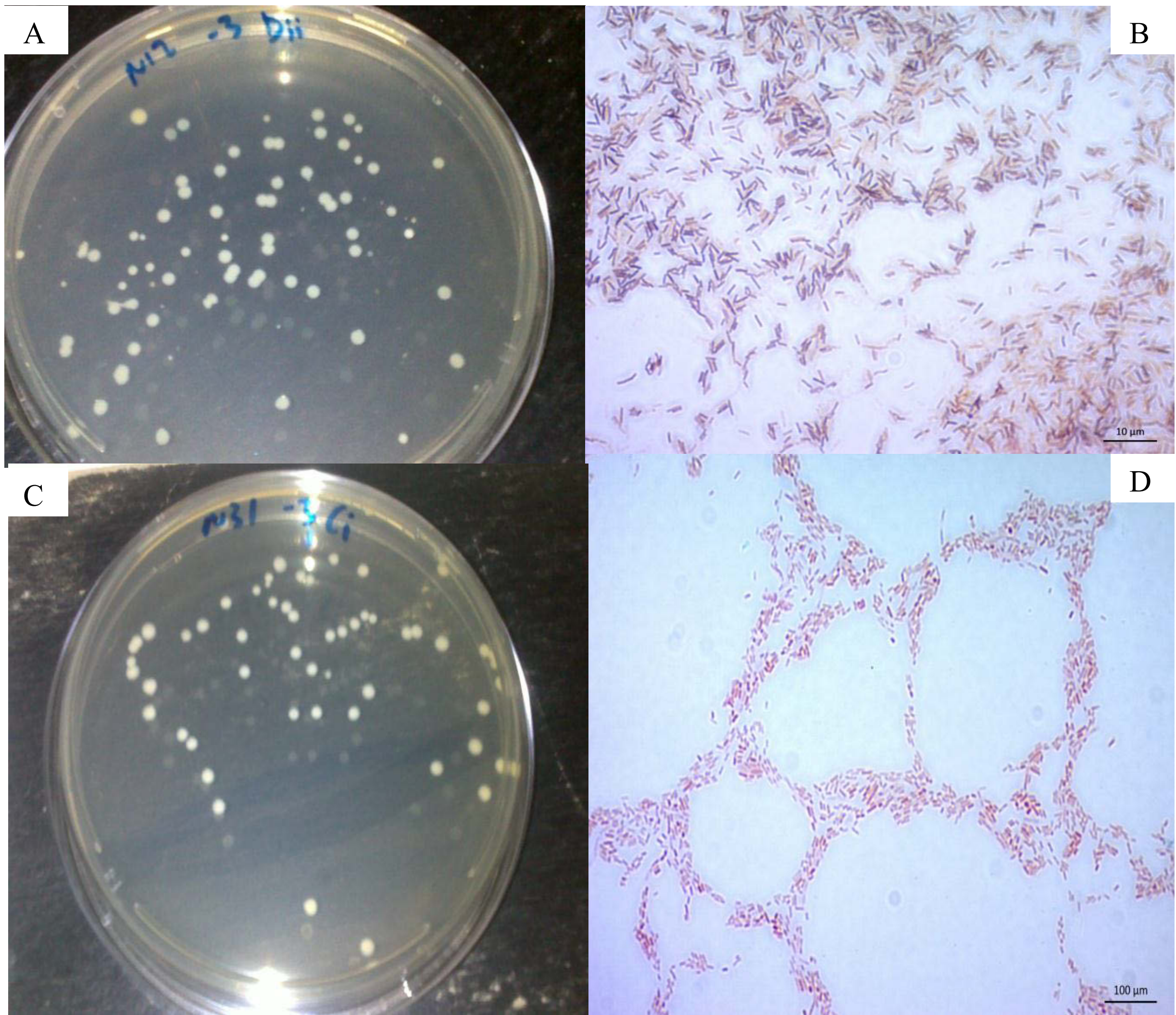
7. APPENDIX

Appendix 1 White colonies (A) observed in both trials, but predominantly in trial 2 and Gram-stain of these colonies, showing short Gram-positive rods (B). Cream colonies (C) predominantly observed in trial 1, Gram-stain of the colonies showing short Gram-positive rods (D) (X1000).



Appendix 2 Counting of bacterial colonies using a colony counter, Pietermaritzburg, South Africa.

Appendix 3 Table showing factors for constructing variables control charts (Montgomery, 2009).

Factors for Constructing Variables Control Charts

Observations in Sample, n	Chart for Averages					Chart for Standard Deviations						Chart for Ranges				
	Factors for Control Limits			Factors for Center Line		Factors for Control Limits				Factors for Center Line		Factors for Control Limits				
	A	A_2	A_3	c_4	$1/c_4$	B_3	B_4	B_5	B_6	d_2	$1/d_2$	d_3	D_1	D_2	D_3	D_4
2	2.121	1.880	2.659	0.7979	1.2533	0	3.267	0	2.606	1.128	0.8865	0.853	0	3.686	0	3.267
3	1.732	1.023	1.954	0.8862	1.1284	0	2.568	0	2.276	1.693	0.5907	0.888	0	4.358	0	2.574
4	1.500	0.729	1.628	0.9213	1.0854	0	2.266	0	2.088	2.059	0.4857	0.880	0	4.698	0	2.282
5	1.342	0.577	1.427	0.9400	1.0638	0	2.089	0	1.964	2.326	0.4299	0.864	0	4.918	0	2.114
6	1.225	0.483	1.287	0.9515	1.0510	0.030	1.970	0.029	1.874	2.534	0.3946	0.848	0	5.078	0	2.004
7	1.134	0.419	1.182	0.9594	1.0423	0.118	1.882	0.113	1.806	2.704	0.3698	0.833	0.204	5.204	0.076	1.924
8	1.061	0.373	1.099	0.9650	1.0363	0.185	1.815	0.179	1.751	2.847	0.3512	0.820	0.388	5.306	0.136	1.864
9	1.000	0.337	1.032	0.9693	1.0317	0.239	1.761	0.232	1.707	2.970	0.3367	0.808	0.547	5.393	0.184	1.816
10	0.949	0.308	0.975	0.9727	1.0281	0.284	1.716	0.276	1.669	3.078	0.3249	0.797	0.687	5.469	0.223	1.777
11	0.905	0.285	0.927	0.9754	1.0252	0.321	1.679	0.313	1.637	3.173	0.3152	0.787	0.811	5.535	0.256	1.744
12	0.866	0.266	0.886	0.9776	1.0229	0.354	1.646	0.346	1.610	3.258	0.3069	0.778	0.922	5.594	0.283	1.717
13	0.832	0.249	0.850	0.9794	1.0210	0.382	1.618	0.374	1.585	3.336	0.2998	0.770	1.025	5.647	0.307	1.693
14	0.802	0.235	0.817	0.9810	1.0194	0.406	1.594	0.399	1.563	3.407	0.2935	0.763	1.118	5.696	0.328	1.672
15	0.775	0.223	0.789	0.9823	1.0180	0.428	1.572	0.421	1.544	3.472	0.2880	0.756	1.203	5.741	0.347	1.653
16	0.750	0.212	0.763	0.9835	1.0168	0.448	1.552	0.440	1.526	3.532	0.2831	0.750	1.282	5.782	0.363	1.637
17	0.728	0.203	0.739	0.9845	1.0157	0.466	1.534	0.458	1.511	3.588	0.2787	0.744	1.356	5.820	0.378	1.622
18	0.707	0.194	0.718	0.9854	1.0148	0.482	1.518	0.475	1.496	3.640	0.2747	0.739	1.424	5.856	0.391	1.608
19	0.688	0.187	0.698	0.9862	1.0140	0.497	1.503	0.490	1.483	3.689	0.2711	0.734	1.487	5.891	0.403	1.597
20	0.671	0.180	0.680	0.9869	1.0133	0.510	1.490	0.504	1.470	3.735	0.2677	0.729	1.549	5.921	0.415	1.585
21	0.655	0.173	0.663	0.9876	1.0126	0.523	1.477	0.516	1.459	3.778	0.2647	0.724	1.605	5.951	0.425	1.575
22	0.640	0.167	0.647	0.9882	1.0119	0.534	1.466	0.528	1.448	3.819	0.2618	0.720	1.659	5.979	0.434	1.566
23	0.626	0.162	0.633	0.9887	1.0114	0.545	1.455	0.539	1.438	3.858	0.2592	0.716	1.710	6.006	0.443	1.557
24	0.612	0.157	0.619	0.9892	1.0109	0.555	1.445	0.549	1.429	3.895	0.2567	0.712	1.759	6.031	0.451	1.548
25	0.600	0.153	0.606	0.9896	1.0105	0.565	1.435	0.559	1.420	3.931	0.2544	0.708	1.806	6.056	0.459	1.541

For $n > 25$.

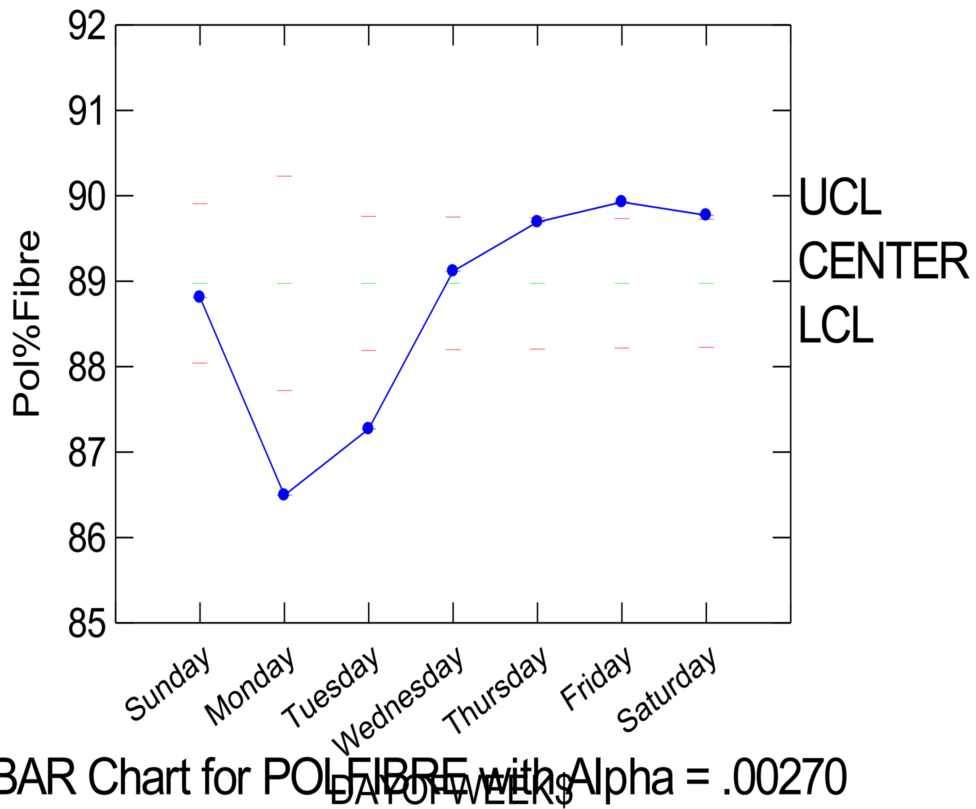
$$A = \frac{3}{\sqrt{n}} \qquad A_3 = \frac{3}{c_4\sqrt{n}} \qquad c_4 \cong \frac{4(n-1)}{4n-3}$$

$$B_3 = 1 - \frac{3}{c_4\sqrt{2(n-1)}} \qquad B_4 = 1 + \frac{3}{c_4\sqrt{2(n-1)}}$$

$$B_5 = c_4 - \frac{3}{\sqrt{2(n-1)}} \qquad B_6 = c_4 + \frac{3}{\sqrt{2(n-1)}}$$

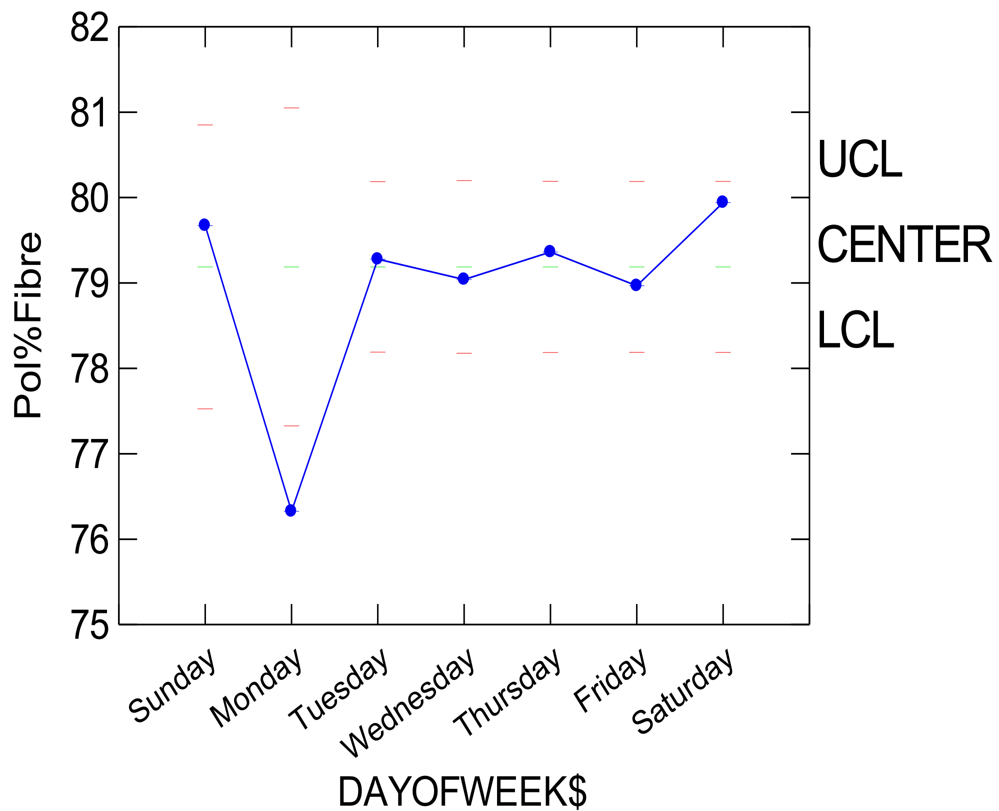
X-BAR Chart for POLFIBRE with Alpha = .00270

Appendix 4 QCC for *Pol % Fibre* for Empangeni Central seasons 2004 to 2009.



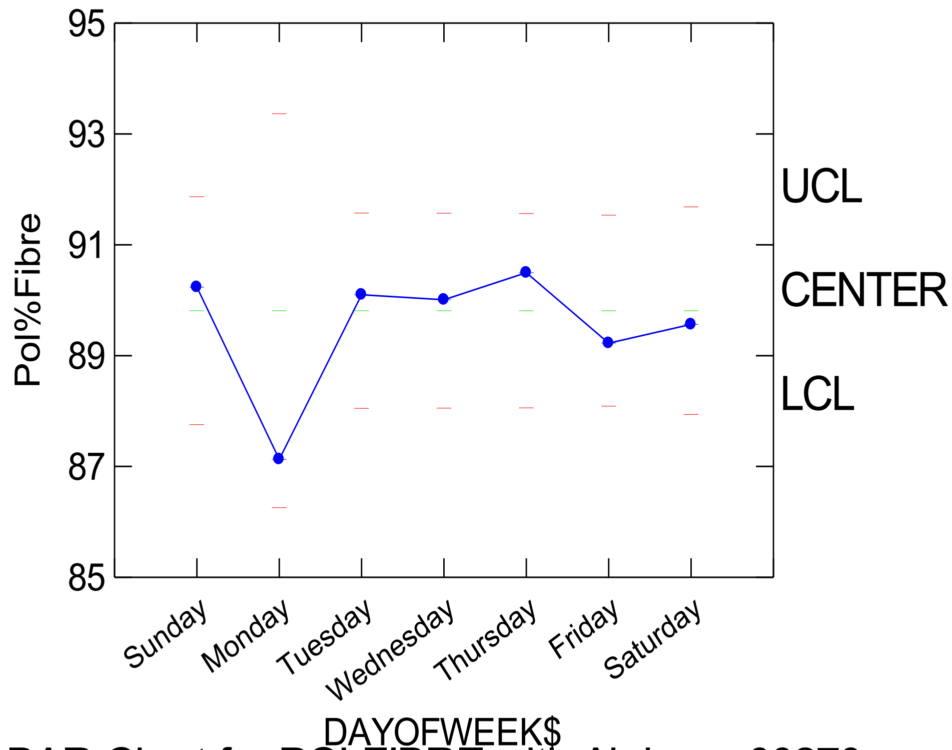
X-BAR Chart for POLFIBRE with Alpha = .00270

Appendix 5 QCC for *Pol % Fibre* for Empangeni East seasons 2004 to 2009.



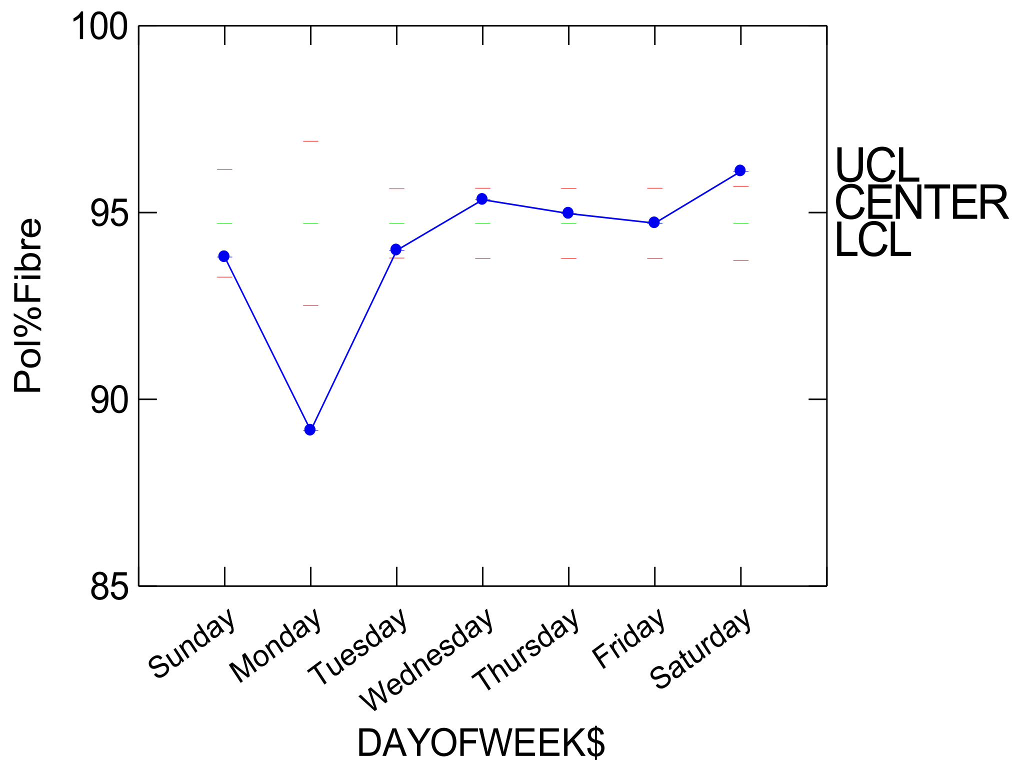
X-BAR Chart for POLFIBRE with Alpha = .00270

Appendix 6 QCC for *Pol % Fibre* for Empangeni West seasons 2004 to 2009.



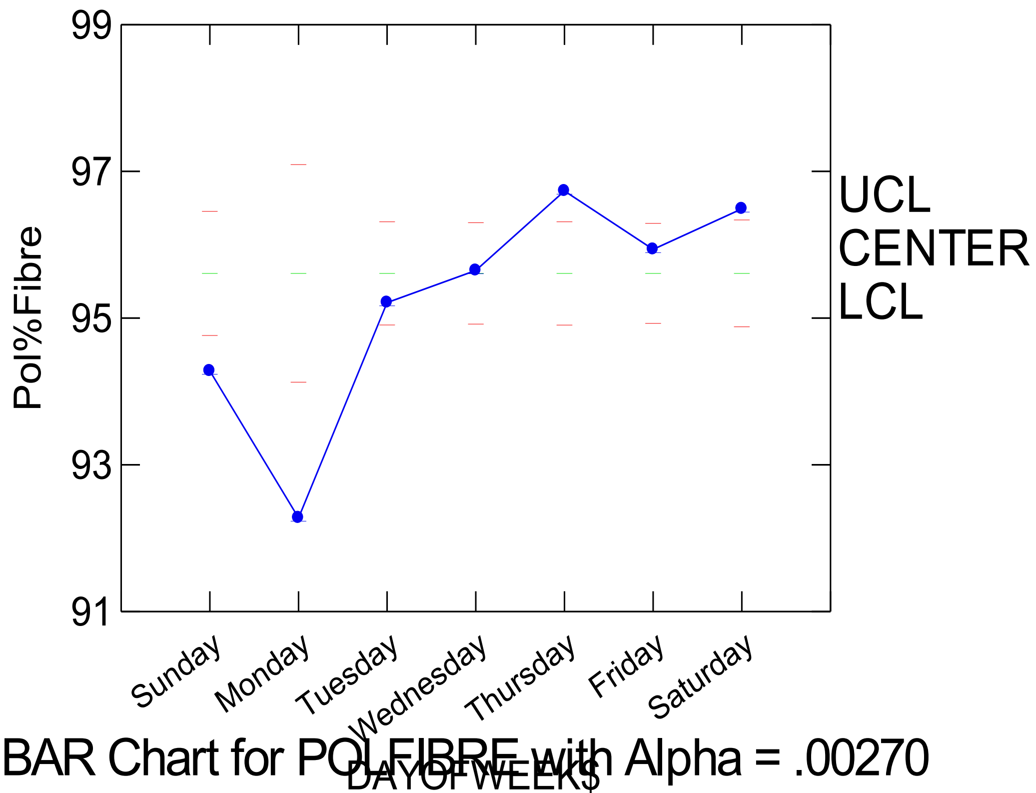
X-BAR Chart for POLFIBRE with Alpha = .00270

Appendix 7 QCC for *Pol % Fibre* for Felixton Flats seasons 2004 to 2009.



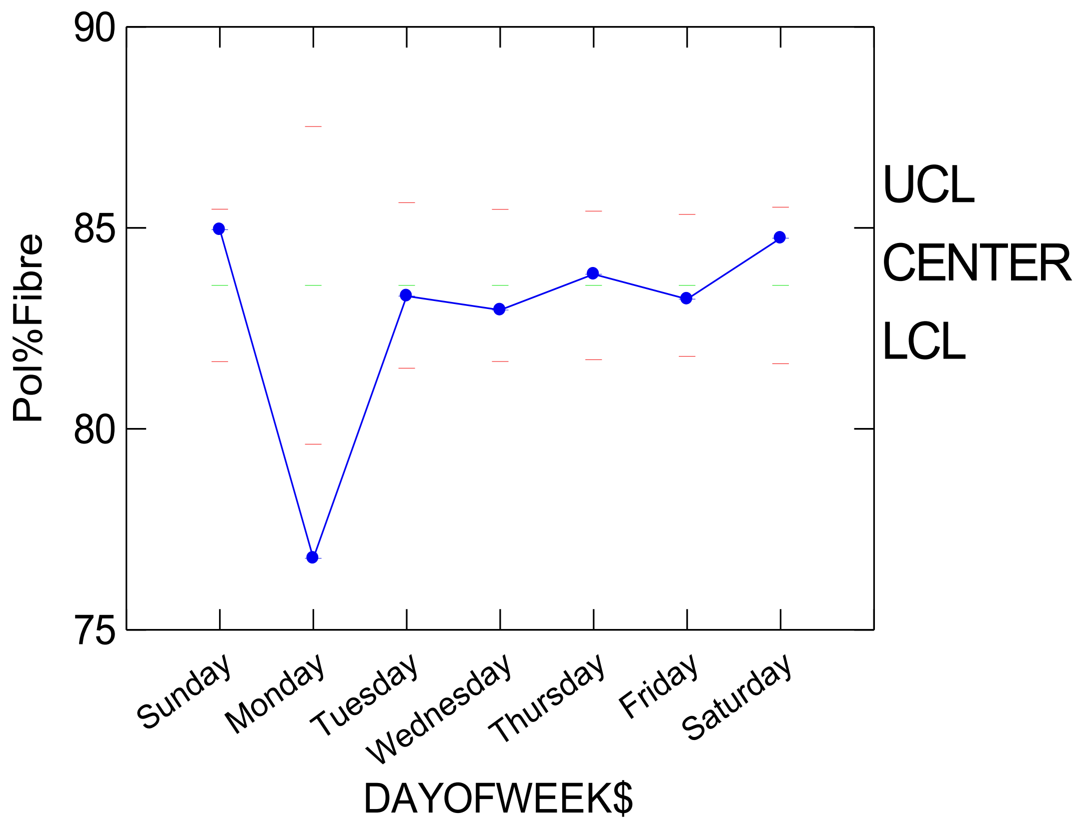
X-BAR Chart for POLFIBRE with Alpha = .00270

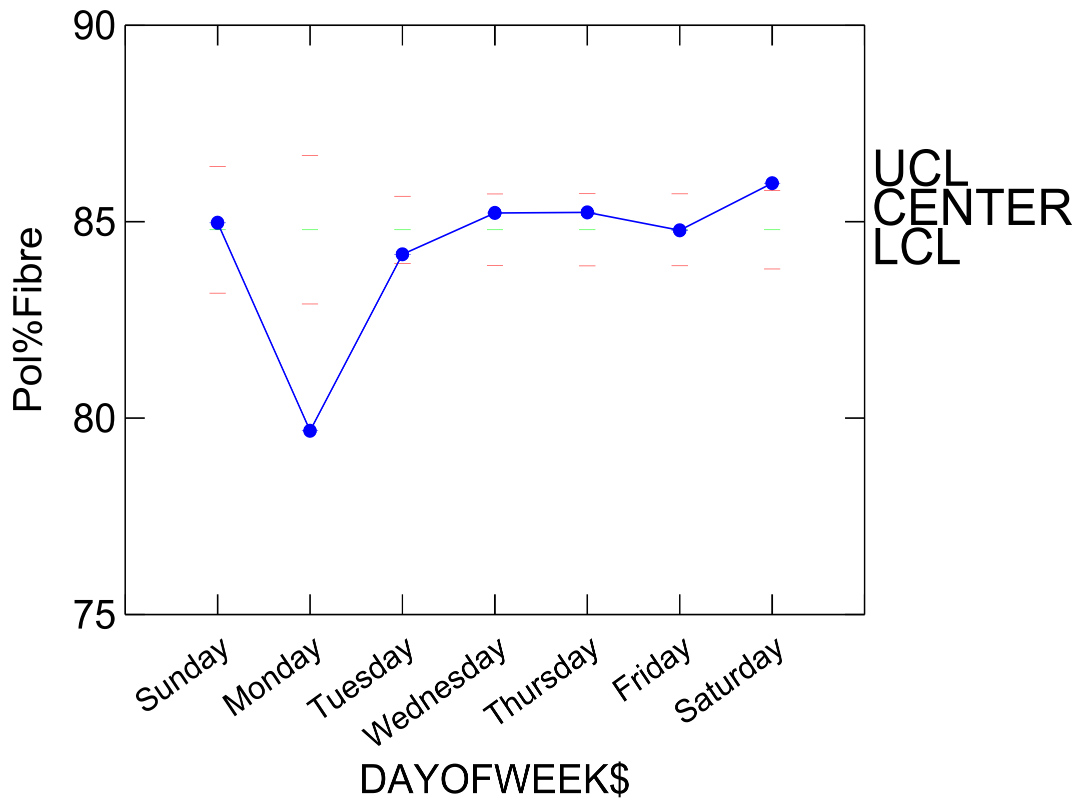
Appendix 8 QCC for *Pol % Fibre* for Heatonville scheme seasons 2004 to 2009.



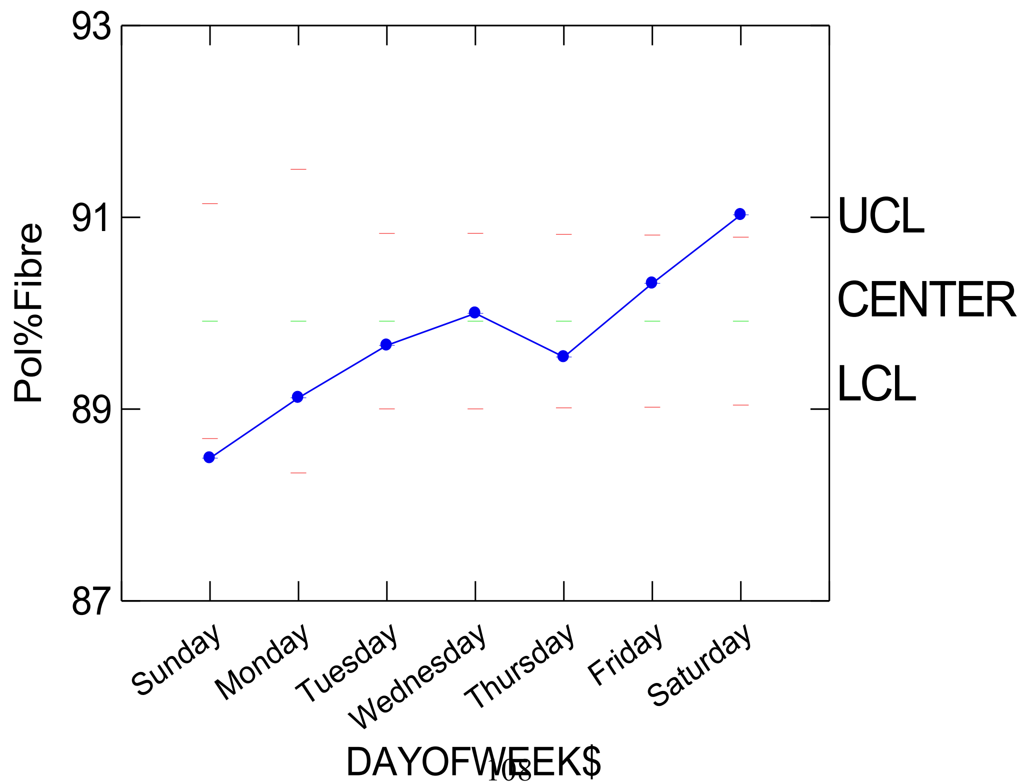
X-BAR Chart for POLFIBRE with Alpha = .00270

Appendix 9 QCC for *Pol % Fibre* for Heatonville Riparian seasons 2004 to 2009.





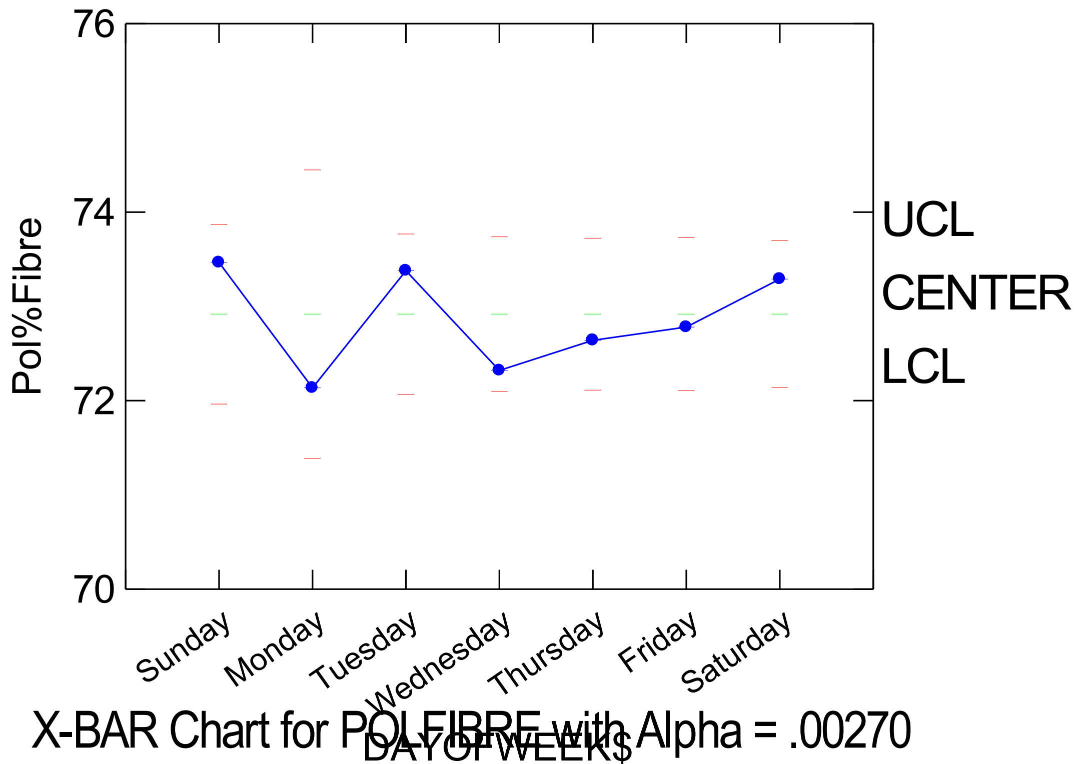
Appendix 10 QCC for *Pol % Fibre* for Felixton hills 2004 to 2009.



Appendix 11 QCC for *Pol % Fibre* for Mtunzini 2004 to 2009.

X-BAR Chart for POLFIBRE with Alpha = .00270

Appendix 12 QCC for *Pol % Fibre* for Mposa 2004 to 2009.



X-BAR Chart for POLFIBRE with Alpha = .00270

Appendix 13 QCC for *Pol % Fibre* for Northern areas 2004 to 2009.