Wheat processing quality: its assessment and potential for measurement at the grain silo

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Abstract

Wheat processing quality can be loosely defined as the suitability of grain for a particular end-use Thus, the physical and chemical characteristics required for products such as pan breads, cookies and white salted noodles are quite different. One of the major changes that have occurred in the handling of grain in Australia and other countries over the last few decades has been a significant increase in the number of segregations of grain into separate storages, corresponding to grain intended for different end-uses. Although an increased number of segregations increases the storage and handling costs of the grain, this cost is usually more than offset by the ability of much of the grain to command a premium price. In most cases, the actual processing quality of the parcel of grain is not measured, but rather the variety, protein content and physical characteristics such as moisture content and grain size and density While Near-Infrared (NIR) Spectroscopy has been very widely used for estimation of grain protein content, recent results suggest that the content of polymeric glutenin proteins, which have a major role in deter-mining processing quality, could be assessed at receival Image analysis or biochemical test methods that could confirm that the correct variety has been declared by the farmer before the grain is binned are also needed. Equally important is knowledge of the possible presence of contaminants or defects which could lead to a down-grading of grain quality. A range of field-use immunoassays has been developed to overcome quality defects, including pre-harvest sprouting, grain protectant and mycotoxin contamination of grain, and these could be extended to the analysis of weed seed contaminants and storage fungi. There is also potential for the technology to be applied to the analysis of raw material factors associated with noodle colour and colour defects, including those arising from the use of red grain. The development and application of the range of current and potential diagnostic testing techniques will be reviewed. In addition, recent results in two important research areas will be discussed, namely, identifying quality changes in wheat during extended storage (and establishing how they arise), and understanding the basis of the non-linear quality responses that are often seen when different wheat varieties are blended.

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Introduction: What is Wheat Quality?

Wheat is used for a bewildering range of end-products, ranging from pan breads, various Arabic flat breads to various noodle types (including white salted, yellow alkaline, regional preferences), cakes and cookies. As a major exporter of wheat (only 15-20% is consumed locally), Australia needs to consider the quality requirements of its major export markets in Asia and the Middle East as well as domestic requirements. Wheat quality can broadly be described as suitability for particular end-products, or in other words, the ability of the grain to meet the requirements of the processor For example, medium-to-high protein hard-grained wheat which producing doughs of medium-to-high strength is usually preferred for pan breads, while for sweet biscuits, low protein, soft-grained wheat with low gluten strength is preferred For white salted noodles, starch of high pasting viscosity is preferred, along with low amylose contents Overall, however, the two most important factors are protein content (Finney and Barmore, 1948) and variety (Zhu et al., 1996; Skerritt, 1998), which largely determine protein and starch quality and hardness, but a range of other physical and chemical characteristics are important. Some are determined genetically (through the variety or cultivar of the wheat) and others are determined by the growth environment Important environmental factors include soil type and fertility, fertiliser use, water availability and temperature and environmental stresses during grain filling (Anderson et al., 1997).

Segregation and Changes to Grain Handing Practices in Australia

For many years, Australian wheat that exceeded certain minimum standards was classified as FAQ (Fair Average Quality) and any particular grist could include both hard and soft grained types and a range of protein contents. Some specialty flours were produced, but wheat was basically treated as a bulk commodity and special quality characteristics of individual varieties could not be exploited Apart from the move to bulk handling, one of the main changes to grain handling over the last 30 years has been the introduction of different degregations at silo (elevator) receival of the grain. In the late 1950's, marketers began to segregate hard wheat from soft wheat in Australia, and in 1974 the FAQ system was finally discontinued (Simmonds, 1989). This enabled grain of different end-use qualities to be binned and stored separately, and for growers to receive different prices for grain of different grades. The main factors determining grading of grain in Australia currently are variety, protein content, grain size, and defects such as unmillable material, staining and pre-harvest sprouting Segregation comesat a cost to the handling companies but this can be more than offset by increased returns to marketers and to growers

In Australia, different premiums apply to grain of different quality types, and obviously different varieties are more or less suited for different environments. Wheat growers in many areas have a choice, mainly determined by the variety they sow and the management practices they use, as to whether to grow a lower-premium variety that is higher yielding, or to grow a premium-attracting wheat that may be lower in yield. There are financial incentives for end-use quality, although at present the premiums are often not high enough to favour high-quality over high-yielding varieties. In addition, factors such as a dry finish to the season or wet harvests can cause significant downgrading of premium wheats through small grain size or pre-harvest sprouting, respectively. This review will focus on testing methods that are currently carried out at receival of grain at the silo (elevator) or flour mill, as well as describing some newer methods that we are developing or plan to develop in the near future. There will always be some resistance to the introduction of new testing methods unless they can improve the efficiency of grain segregation without a significant impost in time or labour at the silo or mill Thus our focus is on obtaining a better understanding of quality changes in storage and the development of new testing methods that could either improve current measurements, enable parameters to be measured at receival instead of being done detrospectively in the laboratory, or enable the measurement of parameters of key economic value to be measured.

Measurement of Physical Characteristics of Grain

Grain hardness is a major determinant of the end-use of wheats since it affects the degree of mechanical damage to the starch during milling and the amount of water that is taken up by the grain. Pan breads, for example usually require hard grained wheats, while sweet cookies require soft grain Some noodle types are best prepared from hard grained wheat while others are best prepared from soft wheat. Hardness can be measured either by a grinding time test or by near-infrared (NIR) spectroscopy (since NIR can assess differences in particle size between samples). Grain density and size can be assessed physically by measurement of hectolitre weight and thousand kernel weight, respectively. Wheat are divided into red- and white-grained types. The red grained wheat are less suitable for maximizing the yield of white flour for products which require brightness and whiteness and low flour ash, such as steamed breads and salted noodles. Typically 1.5-2% lower flour yields can be expected from red wheat compared to white wheat for similar flour colour Despite the apparent obviousness suggested by the terms red and white, many red- and white-grained varieties cannot be reliably discriminated by eye. One way of enhancing their discrimination, although it may not be practical for silo testing, is to soak the grain in sodium hydroxide solution (De Pauw and Mc Caig, 1988) Recent CSIRO research has shown that either near-infrared transmission analysis in the 800-1200nm range (Ronalds and Blakeney, 1995) or use of a colour meter using a combination of transmitted light and reflectance modes (Bason et al., 1995) are reliable approaches for discrimination of red and white grained wheat. Alternatively, a simple biochemical test specifically targetting the colour components (in the bran contamination in the flour) could be developed; this would also have the advantage of being able to discriminate flours derived from red and white wheats

Use of NIR Methods

Grain protein and moisture content

Over the last 2 decades, NIR methods have become widely adopted at mill or silo receival for the determination of grain protein content, and the results of this testing have been used as a primary means of grading wheat. Grain moisture and hardness are also standard parameters that are routinely measured by NIR. One of the major advances in recent years has been the ability to analyze whole grain, meaning that no sample preparation is required-a grain sample can be simply tipped into the top of the machine and results generated automatically. NIR works in a similar manner to any other spectroscopic technique-different chemical groups in the sample absorb radiation at characteristic wavelengths and the extent of absorption depends on the concentration of the analyte.

Other potential applications

The existence of NIR equipment at many mills and silo receival sites along with the lack of sample preparation required by users of NIR, led us to explore whether we could utilize the technique for assessment of processing quality rather than merely for protein content Correlation between particular dough properties and NIR spectra have been reported in several independent studies in the scientific literature (Williams et al., 1988; Delwiche and Weaver, 1994; Delwiche et al., 1998), but the results of these studies have not been widely replicated and are thus not used in routine quality evaluation. The chemical and spectroscopic principles behind obtaining these reported correlations have not been systematically investigated, and because the wheat sets used in these studies have wheat had uncontrolled variation in variety and protein content, the correlation have not been transferrable between different environments or sets of wheats. Since variation in dough properties is largely derived from variation in the content and composition of gliadin (monomeric) and glutenin (polymeric) proteins, we aimed to quantify these components spectroscopically. We found that purified gliadin and glutenin had distinct spectra (Uthayakumaran et al., 1998), and while spectral masking by the large excess of starch present in the grain meant that single wavelengths could not be used for the quantification, it was possible to quantify gliadin and glutenin in the sample by use of the sample's entire NIR spectrum Good correlation were obtained between the quantities of the polymeric glutenin protein measured by size-exclusion high performance liquid chromatography (HPLC) and the amount predicted by NIR (Wesley et al., 1998) Glutenin content is a major factor affecting dough properties and in turn, we were able to predict some of the key dough properties of the sample using NIR measurement of glutenin in whole grain, especially if we took variation in total protein content into account.

While more work needs to be done, the potential outcome is the development of NIR-based quality predictions that are unaffected by site, season or grade, enabling the use of NIR in selection for processing quality in breeding If robust predictions of dough properties are able to be made by NIR spectral analysis, the already wide availability of NIR equipment in many countries may allow the use of NIR to measure grain quality at silo or mill receival segregation rather than mere variety and protein content. This would be very valuable since environmental effects during crop development can lead to very significant variation in grain quality.

Flour Colour Characteristics and Potential Defects

Colour (high whiteness in the case of steamed breads and salted noodles, yellowness in the case of alkaline noodles) and brightness (all product types) are critical factors which determine the suitability of particular wheat batches for use in these end-products (Miskelly, 1984; Huang et al, 1995) Apart from red versus white grain, major factors that have been established as having an effect on brightness and colour of these products are yellow pigments and their precursors and the presence of bran and other specks. The yellow colour of alkaline noodles is an important positive quality characteristic It is enhanced by addition of alkali salts to flour during production of some types of noodles. On the other hand, yellow flour colour is a negative characteristic for steamed buns, salted noodles and pan breads. Two groups of compounds are involved in yellow flour colour, water-soluble flavonoids and yellow-coloured carotenoids (Belitz and Grosch, 1987) Most of current researches have focussed on estimating the value of a colour meter test on noodle sheets or a flour-water slurry An alternative would be a simple diagnostic test (possibly using an antibody) for the yellow colour components in wheat Such a test would also be simple to perform and would not need expensive equipment. Fleckiness (or speckiness) in end-products such as steamed breads or noodle sheets is a major defect, and can be caused by either variation in the wheat raw material or poor flour milling practice Recently, image analysis technology (* cranscan) has been developed for quantification of bran particles, but it is too expensive for use in developing countries (Millar et al, 1997). Fleckiness caused by variation in the wheat raw materials is often due to varietal and growth-environment differences in polyphenol oxidase enzyme levels Several approaches for screening for this enzyme in breeding programs have been introduced, but this should be extended to receival testing.

Determination of Variety / Quality Type

The variety (genotype) of wheat sample is usually the principal determinant of appropriate end-use for the sample. As a result, there has been substantial research and development on reliable methods for the determination of variety (reviewed in Wrigley, 1995) Laboratory methods for variety identification typically exploit genetic variation in seed storage protein (gliadin and glutenin subunit) composition, and include acid-buffer electrophoresis of gliadins, sodium dodecyl sulfate polyacrylamide gel electrophoresis, capilliary electrophoresis or reversed-phase HPLC of gliadins and glutenin subunits. Some DNA-based methods utilizing microsatellite profiles, RFLP or specific PCR markers are also in use; these target at both storage protein and other genes. While it is essential to have laboratory reference methods for variety identification, it would be extremely valuable, if a rapid field-based test for differentiating and identifying wheat varieties could be developed for use at the mill or silo. Particular varieties within a general wheat grade can significantly differ in their suitability for use in particular end-products. For example, only certain Australian Standard White (ASW) varieties are suitable for noodles With the advent of breeders' plant variety rights, several countries are introducing end-point royalties for specific varieties. There is therefore a need to avoid the risk of false variety declarations by farmers. Image analysis of grain shape characteristics is a potentially rapid approach to this problem that requires little sample preparation To date, there has been some success in its use to distinguish different wheat classes and grades (Sapirstein, 1995), but less in the identification of particular varieties from a large number of possibilities The cost of the equipment and software also limits its wider application at flour mills. A new research project within the Quality Wheat CRC aims to develop a test with the following characteristics: inexpensive test, results in 5 minutes, readable by eye by users with minimal training, and results unaffected by environmental variation in grain protein content. Knowing the identity of the variety is only half the story; the key challenge is to correctly match the variety to an optimal end-use. In Asian products area, this has been an active area for Australian, Canadian and US grain laboratories, anxious to develop or expand export markets. However, in Asian wheat-growing countries such as China, India and Pakistan, there is the need to better develop this information for their locally-grown wheats

Contaminants

It is necessery to carry on tests for grain protectants and mycotoxins. The grain protectant insecticides include certain degradable organophosphates, car-bamates, pyrethroids and insect growth regulators which are intentionally applied to grains after harvest and before either bulk or bagged storage. Strict Maximum Residue Limits (MRL) or trade tolerances apply to the levels of the compounds that can be permitted to remain before the grain is marketed. Our research aimed to develop and apply rapid, simple and inexpensive tests for detection of residues of key pesticides in wheat and barley grain and grain products by use of modern antibody-based and enzymatic techniques. The pesticides that we targetted include organophosphates (fenitrothion, chlorpyrifos-methyl and pirimiphosmethyl), synthetic pyrethroids (bioresmethrin, phenothrin, deltamethrin, cyfluthrin), carbaryl and methoprene. These tests, which are now commercially available, were designed to enable either rapid field testing to be done at the silo storage level or using microwell ELISA assays, in small company and regional laboratories where either instrumental pesticide analyses would not be feasible or equipment and staff to perform these analyses would not be available. Both formats enable quantitative pesticide analysis Along with the development of simple test methods for the analysis, it was critical to develop simple methods for either laboratory or field extraction of the pesticides for use in the antibody tests. We were fortunate that most of the residue remained on the outer layers of the grain, and that earlier research had shown that mere soaking of whole grain or flour in methanol for 48 hr could quantitatively extract residues For rapid silo (grain elevator) tests, this method was obviously too slow, but research indicated that 2 min blending of ground grain in a stainless steel Waring blender provided similar extraction efficiencies The assays for each agrochemical have been validated using wheat and barley grain samples with incurred pesticide residues In each case, good correlation have been obtained between the new test and laboratory instrmental methods were obtained (Skerritt et al., 1992 a, b; Lee et al., 1998)

ELISA test kits detecting many of the major mycotoxins are also commercially available in a number of laboratory and field formats (Morgan, 1995) Compared with pesticides, the synthetic chemistry for development of haptens for immunoassays is usually more straightforward (since many of the mycotoxins have alcohol or ketone groups that are suitable for derivatisation), and has been published, so that production of these assays by developing country scientists who cannot afford US or European manufactured kits should be straightforward Some of the main challenges in mycotoxin analysis are that: 1. assay detection tolerances required vary significantly between markets; 2 the distribution of toxins in grain is very uneven, making sampling for analysis and application of management strategies very difficult; and 3 some toxins are still poorly characterized One of the main remaining targets for assay development are the Alternaria toxins, which are suspected of contributing to poor animal performance and have caused significant mortality in chickens in experimental feeding studies (Webley et al, 1997) *Alternaria alternata* produces toxins such as alternariol, its monomethyl ether, altenuene and altertoxins I, II and III, which are mutagenic; tenuazonic acid which is tumorigenic; and AAL toxin, a potential carcinogen In contrast to most other mycotoxins, toxins from Alternaria appear during crop development, meaning that the problem cannot be eliminated through the use of improved storage practices

Other Sources of Downgrading

Pre-harvest sprouting

Rain at harvest seriously affects the quality of grain Weather-damaged wheat has a significantly lower market value because bread products have poor colour, loaf structure, volume and crumb texture, while noodles have poor colour and cooking characteristics. The Falling Number test is used around the worldwide to gauge α amylase activity in wheat and wheat flour due to sprout damage. The method works on the principle that the presence of α amylase causes gelatinized starch to be reduced to sugars, thereby losing viscosity Lower viscosity is reflected in a lower Falling Number While the test is reasonably sensitive and reliable, low sample throughput and the need for expensive instrumentation limit its use at mills and silos We have developed and alternative, simple field test for the detection of pre-harvest sprouting which also measures amylases in the grain (Skerritt et al., 1997) However, it uses a disposable test card and costs only a few dollars per test The test begins by grinding wheat samples. With a scoop provided in the kit, ground grain sample is transferred to individual extraction tubes A salt solution is added and the tubes are briefly shaken by hand The wheat extract is then spotted onto a test card which contains a gold complex antibody that identifies the amylase enzyme. The card is closed and left 5 minutes; this allows the gold complex (which is pink-purple in colour) to move up a test strip by capillary action If the enzymes are present, the gold-antibody-amylase complex is captured by another antibody printed onto the card, and a pink-purple line appears. The intensity of the line is proportional to the extent of pre-harvest sprouting A portable reader is under development to measure the intensity of the test band We expect that this will be especially useful at silos.

Weed seed contaminants

A major concern of grain handlers and exporters is to conform to very strict maximum tolerances for weed seed contaminants These tolerances are imposed partly because of quarantine or noxious weed concerns of importing countries, and partly because of potential consumer exposure to alkaloids and other seed toxins In addition, weed seeds can cause problems for the local feeds market, where toxicity and/or feed refusal (off taste rejection) can occur. The analysis for weed seeds is currently done by eye, but it is difficult and unreliable for several reasons. It is a specialized job, so it really is only possible to police major violations at silos and in trading The seeds come in different shapes and sizes and the logistics of being able to detect contaminations down to the action level (which is under 2 seeds per kg of grain for some weed species) are daunting. There is thus a need for objective test methods for weed seeds. While image analysis methods have been proposed, and alternative may be a simple biochemical test (e.g immuno-chromatography or an ELISA) that could, at the required sensitivity, detect any of the problem seeds

Quality Changes on Storage

Most post-harvest storage research has focussed on minimizing grain losses that would result from insect infestation While there are many anecdotal reports describing differences in the processing properties of grain that has been stored for several months compared with freshly harvested grain, there is little understanding of the nature and basis of storage changes. In a Quality Wheat CRC project, several hundred kilograms of grain were stored under controlled conditions, with the aim of identifying the factors that cause quality changes following harvest (Haigh et al , 1997). Dough from wheat stored at 30-35℃ showed comparatively longer development time, lower extensibility and higher resistance to extension for dough, and produced loaves with significantly lower volumes than grain stored at lower temperatures. Significant changes became obvious after 140 days at 30℃. No changes were observed during one-year's storage at 4℃ or at 15℃ Experiments using high and low oxygen atmospheres (1% and 21% oxygen) at 30℃, 15℃ and 4℃ found ineffective due to variations in the oxygen concentration of the storage atmosphere This indicates that the oxygen concentration is not rate-limiting in whatever process taking place to cause the quality changes at 30℃. However, the proportion of very high molecular weight protein aggregates increased during storage at 30℃, so the changes are presumed to be oxidative in nature. The results indicate that aeration of grain storage to reduce the temperature of the stored grain would also reduce the rate of the quality changes The success of the storage work at the laboratory scale has warranted experiments in silo storage following the 1998 harvest

Blending of Wheat to Achieve Quality Targets

Almost all wheat maintained in grain storage, milled and processed for consumption are blends of several varieties. However, most of the initial evaluation of wheat by breeders and cereal chemists is performed on pure variety. Despite its practical importance, there is a relatively poor understanding of the relationship between the properties of the individual variety and these of the grain blend. The blending of dissimilar samples of wheat that offers a further mechanism whereby quality specifications may be met, but only if reliable methods are available to predict the outcome of this strategy. Such blending is a relatively simple task when formulating combined grain lots with respect to composition (e g. protein content), because the relationships involved are linear. However, blending to achieve a specific target for other quality characteristics (e. g. dough properties) is difficult, because of the non-linearity of relationships involving such characteristics. This is also a common problem in flour milling, where blending before or after milling is common practice for achieving specific quality targets Because blends of flours with different characteristics do not necessarily behave as the simple sum of the components, any proposed model for the prediction of flour-blend characteristics based on simple addition of component behavior may not be correct. Deviation from a linear relationship between functional properties and the blending formula has been found to be even stronger in the case of flours milled from grain blends In the case of two-component grain blends, it was found that the extent of the differences between the functional parameters of the blend and the values calculated from a linear model related to the differences in grain size and hardness among the components blended Explanations of the non-linearity seem to relate to qualitative and quantitative aspects of flour-protein interactions during processing. A non-linear mathematical model is being developed from the large number of sample combinations analyzed, whereby the functional properties of flour and grain blends may be predicted from the chemical composition of the individual components, together with the milling characteristics of the grain samples.

Conclusion: Opportunities for Research

Postharvest research programs have for a long time sponsored collaborative research with a product storage, drying and contaminant focus There is an interest in more researches now being focussed on the postharvest quality of fruits, vegetables and grains to complement the work on storage contaminants and pathology. As the move towards food self-sufficiency is satisfied and production increases, a key issue in the economic development of many developing countries is improved utilization of domestically produced food raw materials This can foster wealth of the community at large through development of profitable domestic markets that can satisfy the growing urban middle class-these markets also have a focus on processing quality. Here the priority is to develop better, appropriate-technology methods for discriminating grain of different quality types (better degregation) and thus optimizing the match of grain to end-use. This review has described a number of techniques which are already available but require better dissemination, as well as research underway on new approaches and a number of exciting possibilities

A good opportunity exists in China, which produces 100 – 105 million tons of wheat annually Although China is the second largest grain importer next to Japan, importing 20 million tons in 1995, over 95% of grain requirements are grown locally. Wheat is a staple food for much of the Chinese population, especially those in the north. As the standard of living increases and the industry moves towards a market economy, there is an increasing focus on the processing quality of Chinese wheat. Several of the major breeding programs have recently released varieties which have both good agronomic and disease resistance properties, as well as having processing quality that is equivalent to elite Australian or North American wheat varieties. New official flour quality grades have been introduced, after major industrial and government collaborative laboratory trials and objective testing. Several of the mills in major cities are attempting to source premium grain for particular products, especially steamed breads, biscuits and pan breads In the south of China, this is often achieved by use of imported wheat, but in the north this could be achievable through the use of local grain

However, despite these three factors, many of the new premium Chinese wheats are mixed indiscriminantly with poor quality wheats, so that the most appropriate grain is not used for the most appropriate end product. Therefore, although wheat is a staple food for much of the Chinese population, the quality of the wheat-based foods that are consumed is usually somewhat poorer than could be achieved by better utilizing appropriate local grain The main component missing in the move for quality-and one which is critical if quality wheat is to be milled – is the ability to select the most appropriate wheat-that is, in industry terms, to make objective degregrations for grain of suitable processing quality type at the mill or at the grain store. There will be a financial incentive to obtain the most suitable grain, now that many mills are semi-privatised. With more appropriate grain, higher quality baked, steamed and boiled end products can be made In addition, mills are now able to market flour outside the planned (state-managed) economy, and under the existing flour standards, the market price achievable for the flour will depend on which grade standard it meets, which in turn depends on both the quality of the original wheat and how it was milled. The current inability to routinely discriminate high quality wheat from inferior grain may mean that the potential for improved quality products and the resulting economic advantages derived from many of the recent advances in breeding cannot be captured by Chinese mills

References

Anderson, W K , Crosbie, G. B. , and Lambe, W. J , 1997 Production practices in Western Australia of wheat suitable for white, salted noodles. Australian Journal of Agricultural Research 48, 49 – 58

Bason, M. L. , Zounis, S. , Ronalds, J. A. , and Wrigley, C W. , 1995 Segregating red and white wheat visually and with a tristimulus colour meter. Australian Journal of Agricultural Research 46, 89 – 98.

Belitz, H D. and Grosch, W. , 1987 Food Chemistry. Springer-Verlag, Berlin, Germany.

De Pauw, R. M. and Mc Caig, T. N. , 1988. Utilization of sodium hydroxide to assess kernel color and its inheritance in eleven spring wheat varieties. Canadian Journal of Plant Science 68, 323 – 329.

Delwiche, S. R and Weaver, G , 1994 Bread quality of wheat flour by near-infrared diffuse reflectance spectroscopy: feasibility of modeling Journal of Food Science 59, 410 – 415.

Delwiche, S. R , Graybosch, R. A , and Peterson, C. J , 1998. Predicting protein composition, biochemical properties and dough handling properties of hard red winter flour by near-infrared reflectance Cereal Chemistry 75, 412 – 416.

Finney, K F. and Barmore, M A , 1948 Loaf volume and protein content of hard winter and spring wheats. Cereal Chemistry 25, 291 – 312.

Haigh, K. J. , Suter, D. A. I , Higgins, P , O'Riordan, B. , Gras, P. W and Bekes, F , 1997. Effect of wheat storage conditions on bread quality, Proceedings of the 47th Australian Cereal Chemistry Conference, Royal Australian Chemical Institute, North Melbourne, Australia, pp 47 – 51

Lee, N , Beasley, H. L. and Skerritt, J. H , 1998 Development of immunoassays for 'Type II' synthetic pyrethroids: 2 Assay specificity and application to water, soil and grain. Journal of Agricultural and Food Chemistry, 46, 535 – 546

Millar, S. J , Whitworth, M. B. and Evers, A. D , 1997. Image analysis-the prediction and assessment of wheat quality and milling properties In Proceedings of the International Wheat Quality Conference, Manhattan, Kansas, (J. L. Steele and O K Chung, Eds), pp 141 – 152.

Miskelly, D. M. , 1984. Flour components affecting paste and noodle colour Journal of the Science of Food and Agriculture, 35, 463 – 471.

Morgan, M. R. A. , 1995. Monitoring safety of plant foods: Immunodiagnostics for mycotoxins and other bioactive compounds. Chapter 10 in New Diagnostics in Crop Sciences (J. H Skerritt and R. Appels, eds.) CAB International, Wallingford, Oxon, UK pp 215 – 242.

Ronalds, J A. and Blakeney, A. B. , 1995. Determination of grain colour by near infrared reflectance and near infrared transmittance spectroscopy. In Neaping Ahead with Near Infrared Spectroscopy (G. D. Batten, P C. Flinn, L. A. Welsh and A. B Blakeney, eds), Royal Australian Chemical Institute, North Melbourne, Australia pp 148 – 153.

Saperstein, H. D , 1995 Variety Identification by digital image analysis. Chapter 6 in Identification of Food-Grain varieties (C. W. Wrigley, ed), American Association of Cereal Chemists, St Paul, Minnesota, USA, pp 91 – 130.

Simmonds, D. H , 1989 Wheat and wheat quality in Australia, CSIRO, Melbourne, Australia, 299 pp

Skerritt, J H , 1998. Gluten proteins: Genetics, structure and dough quality-a review. AgBiotech News and Information, 10, 247N – 270N

Skerritt, J H , Verity, J C. K. , Hac, L and Hill, A. S , 1997 Development of a simple field test for preharvest sprouting. Proceedings of the 47th Australian Cereal Chemistry Conference, (A. W. Tarr, A S. Ross and C. W Wrigley, Eds.), RACI Melbourne, pp. 470 – 474

Skerritt, J H , Hill, A S , Thwaites, H. L , Edward, S L. and McAdam, D. P , 1992 Enzyme-immunoassay for quantitation of the organophosphate pesticides, fenitrothion, chlorpyrifos-methyl and pirimiphos – methyl in wheat grain and flour-milling fractions Journal of AOAC International 73, 519 – 528.

Skerritt, J. H. , Hill, A. S , McAdam, D. P and Stanker, L. H , 1992 Analysis of the synthetic pyrethroids, permethrin and 1R – phenothrin in grain using a monoclonal antibody-based test. Journal of Agricultural and Food Chemistry, 40, 1287 – 1292

Webley, D. J , Jackson, K L , Mullins, J. D. , Hocking, A. D , and Pitt, J. I , 1997. Alternaria toxins in weather-damaged wheat and sorghum in the 1995 – 1996 Australian harvest Australian Journal of Agricultural Research, 48, 1249 – 1255

Wesley, I. J , Skerritt, J H. , Bekes, F , Cornish, G. B. and Osborne, B G , 1998. Near infrared analysis of a Halberd x Cranbrook doubled haploid sample set, Proeedings of the 48 th. RACI Cereal Chemistry Conference, in press.

Williams, P. C , Jaby El-Haramein, F. , Ortiz-Fereira, G. , and Srivastava, J P , 1988 Preliminary observations on the determination of wheat strength by near-infrared reflectance. Cereal Chemistry, 65, 109 – 114

Wrigley, C W , Ed. (1995) Identification of Food Grain Varieties, American Association of Cereal Chemists, St Paul, MN, USA.

Uthayakumaran, S. , Wesley, I. J , Bekes, F , Osborne, B. G and Skerritt, J. H. , 1998. Near infrared spectral differences between gliadin and glutenin proteins, Proceedings of the 48 th RACI Cereal Chemistry Conference, in press

Zhu, J. B, Liu, G T, Zhang, S Z and Sun, H. , 1996. High and low molecular weight subunits of glutenin and their relationships with wheat quality. Scientia Agricultura Sinica, 29, 34 – 39.