Challenges and opportunities in the use of near infrared for the analysis of intact, high moisture plant products

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Introduction

Near infrared (NIR) spectroscopy has a wide range of advantages for the quality assessment of intact fruits, vegetables and other high-moisture products. It is non-destructive, fast, highly cost effective in appropriate applications and requires no sample preparation or chemical reagents. When contrasted with other uses for NIR, instrument development for high moisture crops has progressed slowly over the past decade due, in part, to a unique set of problems presented by fruits and vegetables. Constraints include: 1) a high product moisture content which absorbs NIR irradiation above 950 nm; 2) substantial variation in product size and shape which results in an inconsistent optical geometry; and 3) variation in the composition of target attributes throughout individual product units.[31] Recent advances have begun to circumvent these constraints, setting the stage for the rapid commercialisation of economically viable applications. The following article reviews current applications and economic considerations relative to instrument development and use.

Fruit and vegetables that lend themselves to quality assessment using NIR tend to have individual product units that are of reasonably high value and a quality attribute(s) that: 1) is important to the consumer's perception of the value of the product; 2) can be measured accurately and 3) can not be readily ascertained by the customer prior to purchase. Critical quality traits tend to be sensory in nature and NIR analysis involves the correlation of spectral data with these attributes. Important traits include internal components modulating taste (sweet and sour), dry matter and internal defects; traits that can not be accurately determined by consumers prior to purchase via external assessment but are extremely important in the consumers eventual satisfaction with the product. Thus, grading fruit and vegetables using NIR provides wholesalers and retailers with the ability to guarantee the quality of the product their customers purchase.

Applications and instruments

Transmission NIR assessment techniques have been established in laboratory settings for a cross-section of quality attributes and crops (Table 1). Quality traits range from acidity to moisture content with soluble solids and dry matter the most frequently measured. In most instances, what is described as sugar content is a measure of soluble solids (Brix). Applications in which commercial instruments are reportedly available are indicated in Table 1. The rapid increase in commercialisation of NIR applications over the past several years has been due, predominately, to four companies (Table 2). Internal defects also represent critical concerns and NIR has been shown to be effective in identifying defects in several products, facilitating the removal of inferior material (Table 3).

Figure 1 illustrates the performance of NIR for three non-destructive quality evaluation applications. The relationship between actual soluble solids in peaches v. that predicted using NIR is given in

Table 1. Potential and current transmission NIR applications and instruments for the non-destructive quality evaluation of high moisture crops. Applications for which instruments are reported to be available are listed in bold (abbreviations: A = acidity, DM = dry matter, F = firmness, M = moisture, OA = organic acids, SS = soluble solids, S = starch, SC = sugar content[a]).

Apricot[18] (OA); Apple[16] (**A**,DM,F,M,**SS,SC**); Cantaloupe[7] (**SS,SC**); Chinese cabbage[14] (SS,SC); Cucumber[17] (DM); Date[9] (M); Honeydew melon[8] (**SS,SC**); Japanese pear (**SS,SC**); Japanese persimmon (**SS,SC**); Kiwifruit[22,26] (DM,SS); Mango[11] (DM,SS); Mushroom[10] (DM); Nectarine[34] (SS); Onion[4] (DM,M,**SS**); Orange[19] (**A,SS,SC**); Papaya[3] (SS); Peach[1,20,28,30,34] (**A,SS,SC**); Pear[21] (**A,SS,SC**); Peppermint[23] (SS,S); Pineapple[11,33] (SS); Plum[25] (SS); Pomelos (**A,SS,SC**); Potato[2,6,12,36] (DM,S); Strawberry[15] (SC); Tangerine (**A,SS,SC**); Tomato[24,29,32] (A,OA); Watermelon (**SS,SC**).

In most instances what is reported as sugars is a measure of soluble solids

Table 2. Companies currently marketing transmission NIR instruments for the non-destructive quality evaluation of fruit and vegetables.

Company	Location
Agricultural Innovations	United States
Fantec	Japan
Mitsui Mining and Smelting	Japan
Sumitomo Metal Mining	Japan

Table 3. The use of transmittance NIR for identifyng internal defects of intact fruit and vegetables.

Product	Disorder	Citation
Apple	Water core	5
Peanut	Mould	13
Potato	Hollow heart	2
Tangerine	Section drying	27

Figure 1(a). The data represents four cultivars (Redhaven, Windblo, Blake and Encore) over three years. The level of precision is sufficient for peaches to be readily sorted into three sweetness classes based upon their soluble solids content (i.e. sweetness).[30]

A major portion of the tomatoes grown worldwide are reduced in volume through dehydration to a paste or sauce. Increasing the fruit solids content from 5% to 6% would represent an increase in value of US$70–80 million a year for the processing tomato industry in the United States alone. The potential to rapidly measure soluble solids would be highly advantageous as a selection tool in tomato breeding programmes focusing on high solids and in processing plants where the price paid for raw products is tied to solids content. In the NIR application illustrated in Figure 1(b), the soluble solids content of the cooked product is predicted from fresh, unprocessed fruit using three different methods of analysis [multiple linear regression, partial least squares regression and neural network].[29]

A third example of an NIR application is for an internal disorder in citrus fruits. A significant problem in citrus fruit is a physiological disorder called dry vesicle. The cells in the vesicles appear to be firm (“granulated”) and when squeezed release virtually no juice. Since the disorder is internal, the fruit can not be separated using external symptoms nor using density differences. Dry vesicle occurs in virtually all citrus crops and increases with the length of storage. Initial work, using the tangerine as a model, has indicated that high quality and defective fruit can be readily separated [Figure 1(c)].[27]

Economic considerations

The ability to accurately determine internal quality attributes in the laboratory or under simulated packing house conditions does not guarantee the commercialisation of an application. Adoption of an application is largely an economic decision involving the cost to benefit ratio for both the instrument manufacturer and the user. Due to questions about the economic viability of NIR grading of high mois-

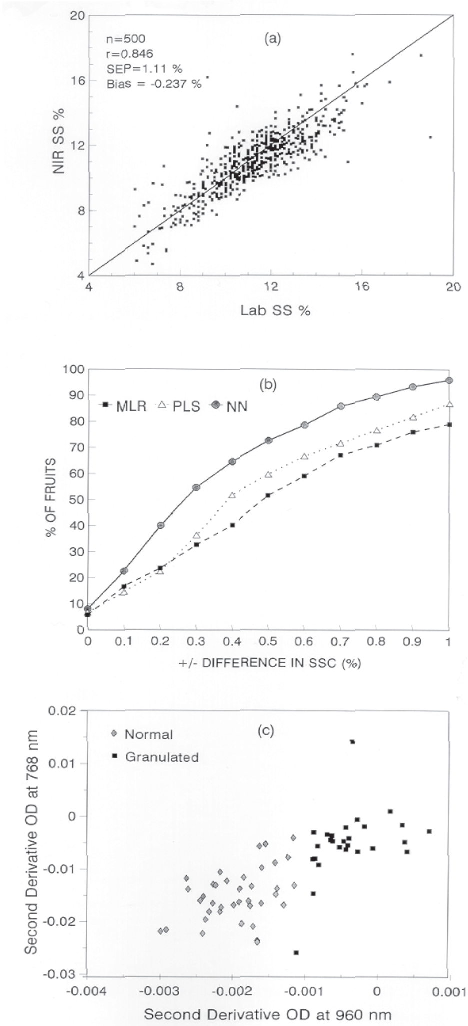

Figure 1. Examples of NIR applications for the non-destructive quality evaluation of high moisture crops. (a) The relationship between laboratory determined peach soluble solids content and that predicted using NIR.[30] (b) Cumulative percentage of tomato fruit plotted against the absolute residual in percent soluble solids as classified by multiple linear regression (MLR), partial least squares (PLS) regression, and neural network (NN) calibrations.[29] (c) The relationship between second derivative optical density values at 768 nm and 960 nm for normal and defective sections of tangerine.[27]

ture crops, the following analysis is presented. Cantaloupe production in the United States is used as the model and estimates of grading costs/fruit are then applied to a cross-section of other fruit crops.

For a manufacturer exploring the possibility of developing an instrument for a specific application, two critical considerations are: 1) how many instruments can be sold and 2) at what price? To address these questions, projections of the cost/fruit for grading cantaloupes for sweetness (soluble solids) in the United States were calculated (Table 4). The annual production of cantaloupes in the United States (1998) was 1.9 million metric tons[35] for which the following criteria were imposed: 1) only one half of the crop is graded; 2) the average weight of an individual fruit is approximately 1.8 kg; 3) the average length of the cantaloupe season for a packing house is 70 days; 4) the packing house lines run 12 hours a day; 5) an NIR instrument has a life expectancy of five years and 6) the instrument maintenance costs are US$5,000 a year. Using these criteria, the number of instruments required to grade one half of the United States cantaloupe crop can be calculated (Table 4). The number of instruments required ranged from 34 to 853, depending upon the rate at which individual product units could be graded. If an instrument has an estimated life expectancy of five years, then the total number of fruit that can be graded/instrument during this time period ranged from 75.8×10^6 for the fastest grading rate (0.2 s per fruit) to 3.0×10^6 for the slowest (5.0 s per fruit).

The second consideration from a manufacturing stand-point is the retail price of an instrument. If the purchase price/instrument is varied from US$50,000 to $500,000 (depreciated over five years), the maintenance costs are $5,000 a year and the rate of grading an individual fruit is varied from 0.2 to 5 seconds, the cost per fruit ranged from $0.00099 for the fastest and least expensive instrument (Table 5) to $0.17301 for the slowest and most expensive instrument. What are realistic grading rates for on-line NIR instruments? Losses in precision with increasing rates vary with the type of measurement

Table 4. The number of instruments required to grade 50% of the U.S. cantaloupe crop.

Grading Time/Fruit (sec)	Total Grading Time[a] (days)	Instruments Required	Total fruit graded in 5 years/instrument ($\times 10^6$)
0.2	2,388	34	75.8
0.5	5,791	85	30.3
1.0	11,942	171	15.2
5.0	59,708	853	3.0

[a] Grading 70 days, 12 hr a day

Table 5. Grading cost per fruit at various instrument purchase prices and grading speeds

Instrument Cost (US$)	Operational Costs (US $)	$/ Fruit[a] @ Various Grading Speeds (seconds)			
		.2	.5	1.0	5.0
50,000	25,000	.00099	.00247	.00494	.02471
100,000	25,000	.00165	.00412	.00824	.04119
200,000	25,000	.00297	.00741	.01483	.07414
500,000	25,000	.00692	.01730	.03460	.17301

[a]Instrument + operational costs / (# fruit in 5 years / instrument) for each grading speed

made (for example, spectral analysis v. single wavelength readings), type of product and other factors. Promotional material for existing instruments give grading rates ranging from 1 to 6 fruit/second, though theoretical rates as high as 20 fruit/second have been proposed.[26] The relationship between speed and accuracy, however, has yet to be adequately explored. For comparison purposes, however, rates from 0.2 to 5.0 seconds/fruit were factored against various instrument costs (purchase + maintenance) to calculate the grading cost/individual fruit (data not presented). The increase in price/kg of fruit, therefore, is a function of the cost of grading and the size of the individual fruit. The cost increase ranged from \$0.00009 kg^{-1} for watermelons at the lowest grading cost/fruit (\$0.001) to \$39.70 kg^{-1} for blueberries at the highest grading cost/fruit (\$0.05). Thus, as the value of an individual fruit declines, grading has a progressively greater impact on the retail price, as illustrated for a cross-section of crops in Figure 2. The percentage increase in retail price per kg ranged from 0.03% for watermelons at the lowest grading price/fruit to 755% for blueberries at the highest grading price per fruit.

Since grading costs are passed along to the consumer as part of the retail price, what is an acceptable additional cost and at what point does it become unacceptable? A wide range of factors modulate the break-point between an acceptable and unacceptable increase in cost and this point is not fixed but changes with time, individual consumer, product, season and other factors. The acceptability of a price increase centres around two questions: 1) what is it worth to consumers to have substandard/defective products removed; and 2) at what price can removal be accomplished?

The value to the consumer is, to a large measure, a function of the relative importance placed upon the quality attribute (for example, is the sweetness of a melon more important than the % dry matter?). Likewise, the probability of purchasing a substandard product is also a factor. As the percentage of

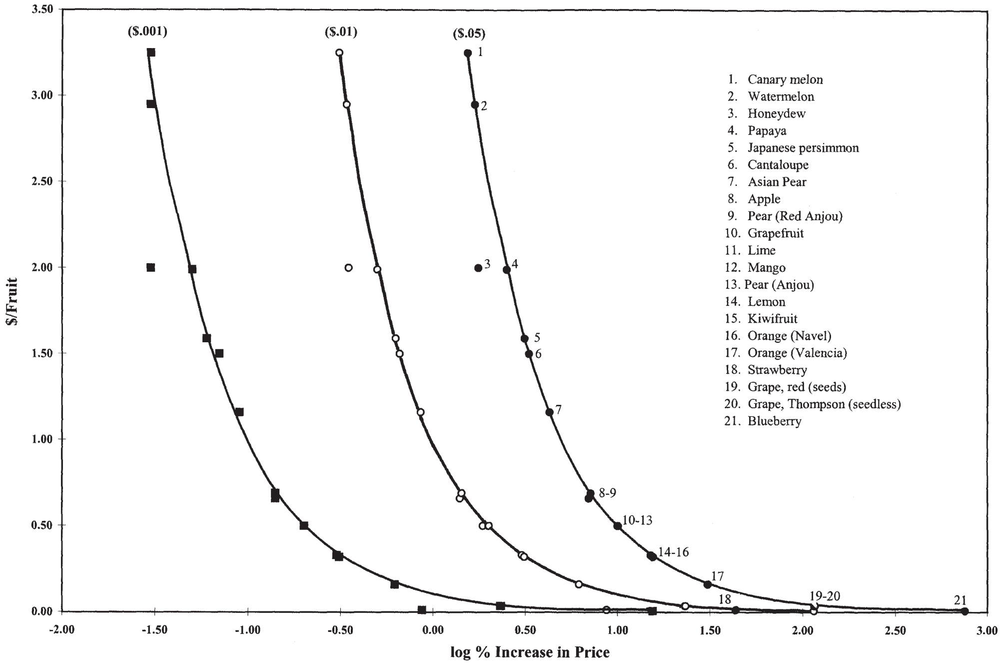

Figure 2. The relationship between the value of individual product units for a cross-section of fruits and the percentage increase in retail price at three grading costs due to NIR non-destructive quality grading.

substandard product units in a particular truck load/field/season increases, the incentive for grading is altered. If only a small percentage of the individual product units are substandard, the cost of removing them may not be justified. For example, removal of 2% substandard fruit is more difficult to justify than 10%, unless the economic impact of their presence warrants removal. Removal of two fruit per hundred at a grading cost of $0.05/fruit, represents a cost of $2.50 for each substandard fruit removed. If the percentage increases to 10% of the fruit, the price drops to $0.50/fruit removed, though the actual grading cost remains constant.

Estimates presented suggest grading costs of < $0.02per fruit for even the higher priced instruments operated at intermediate rates. The cost appears to be within an acceptable range for the majority of the fruit listed in Figure 2, with the exception of blueberries, grapes, strawberries and perhaps several other crops, depending upon their value at the time of grading. Decreasing the cost/fruit through progressively faster and/or less expensive instruments will make grading amenable to crops that are currently at or below the break-point.

Conclusions

Non-destructive quality evaluation of intact fruits, vegetables and other high moisture products using transmission NIR represents a potentially multimillion (US)dollar industry that is at the onset of rapid commercialisation. The use of NIR allows grading based upon internal quality attributes and the removal of substandard product, thus allowing wholesalers and retailers the ability to guarantee the quality of the product their customers purchase. The current availability of the first generation of commercial instruments has greatly stimulated interest in the use and potential of NIR for high moisture crops and is accelerating the rate at which impediments to development are addressed. At prevailing grading rates, a grading cost of < $0.02 a product unit appears to be realistic. The percent increase in retail price due to grading increases with decreasing value/product unit. Resolving current technological and research constraints will open additional applications and increase the precision and value of existing ones. Collectively, non-destructive quality evaluation of intact high moisture crops is nearing the beginning of widespread use in commercial packing houses and fulfilling it's promise of facilitating the delivery of high quality fruits and vegetables to consumers.

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