Spectral bandwidth effect on a *Rhizopus stolonifer* spores detector and its on-line behavior using red tomato fruits

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Hahn, F. 2004. **Spectral bandwidth effect on a *Rhizopus stolonifer* spores detector and its on-line behavior using red tomato fruits**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 3.49-3.54. A fungal disease due to *Rhizopus stolonifer* causes important postharvest losses during shipping and marketing of tomatoes. A conidia detector that can be used on-site, quick, and without liquids was proposed. The feasibility of using near infrared spectroscopy (NIR) for detecting *Rhizopus stolonifer* conidia on red tomatoes was studied acquiring spectra before and after inoculating tomatoes in the laboratory. Discriminant analysis was carried out with 5 nm wide spectral data, and *R. stolonifer* conidia was detected with an accuracy of 78%. The detection accuracy according to the sensing bandwidth was evaluated using 1 and 2 nm width signatures of spore-free and infected tomatoes. The accuracy detection of infected tomatoes increased to 88.92% with 1 nm wide spectral measurements. An automatic conveyor belt was developed to sample the inoculated tomatoes on-line using 1 nm spectral bandwidths acquired with a computerized spectrometer. Four different concentrations were applied and a 92% detection accuracy was encountered for a concentration of 6.5 x 10^4 sporangiospores/mL. **Keywords**: *Rhizopus stolonifer* detection, NIR spectroscopy, discriminant analysis, radiometer, on-line detection.

Une maladie fongique due au *Rhizopus stolonifer* cause d'importantes pertes après la recolte prècose au cours de l' expédition et le marché des tomates. Nous avons proposé un détecteur de conidium qui peut être employé sur place, vite et sans liquides. Le procede d'utilisation du spectre infra-rouge proche (NIR), pour détecter le conidium de *Rhizopus stolonifer,* sur les tomates rouges a été étudiée en ayant des spectres avant, et après l'inocculation des tomates au laboratoire. L'analyse discriminatoire a été effectuée avec 5 nm de large données spectrales et le conidium *R. stolonifer* a été détecté avec une exactitude de 78%. L'exactitude de détection considerant la sensibilite de la largeur de la bande a été évaluée, en utilisant 1 et 2 nm avec les signatures des tomates libres de spores et celles infectées. L'exactitude de détection des tomates infectées a oscillé jusqu'à 88.92%, avec des mesures spectrales de 1 nm de large. Une bande convoyeuse automatique a été développée pour prélever les tomates inoculées, en employant en ligne, des largeurs de bande spectrales de 1 nm acquises avec un spectromètre automatisé. Quatre concentrations différentes ont été apliques, et une exactitude de détection de 92% a été produite pour une concentration de 6,5 x 10^4 sporangiospores/ml. Mots clés: *Rhizopus stolonifer,* détection, NIR, spectroscopie, NIR, analyse discriminante, radiomètre.

INTRODUCTION

Extremely high losses in grains, vegetables and fruits are caused by fungal infection. As much as 30% of the harvested tomato may be lost due to post harvest diseases before reaching the consumer (Boyette et al. 1994). Retail losses of tomato fruit on the greater New York market accounts for 9500 metric tons per year (Ceponis and Butterfield 1979), and 80% of the total loss in prepackaged and loose tomato fruits were dueto Alternaria rot and Rhizopus rot. Mexico, one of the main producers of tomato in the world, planted more than 70,000 hectares in 1997 (Armendáriz 1997), but for successful marketing tomato should have less than one-percent soft or decayed fruit at the shipping point and less than 5% at the destination point (USDA 1991).

Rhizopus rot is a fungal soft rot requiring injuries caused by insects, hail, or cracking for infection to occur. The early appearance of the fungal mycelium is as a fluffy white mass (Agrios 1988). Rot progression is temperature related with rapid fungal growth at 27°C, and no spore germination at 4°C. To minimise the incidence of Rhizopus rot, fruit has to be carefully handled to avoid wounds while keeping clean storage containers, warehouses, and hydrocooling water. Contact infection by which mycelia grow from a rotting fruit to contact and penetrate nearby fruit will involve all the fruit in containers if given sufficient time (Sommer 1982).

Several methods for determining fungal biomass have been proposed (Morgan et al. 1991). Visual techniques are preferred from viable counting methods, as the measurements are rapid, permit the differentiation of dead hyphae, and can monitor fungal coverage on surfaces (Cadwell and Lawrence 1989). The ideal method for detecting infections should require minimum sample preparation and be quick, precise, and inexpensive (Goodacre and Kell 1996). Fungal spore detection is done regularly by isolation on nutrient agar plates, but a simpler method for reducing sampling time would be to use near infrared (NIR) spectroscopy, reflectance being quicker and a more sensitive method than absorbance for microorganism detection (Lanza and Li 1984; Dowell et al. 1998; Aneshansley et al. 1997). *F. oxysporum* was detected on tomates using spectral Fourier signatures with an accuracy of 91.31% (Hahn 2002).

Rhizopus rot is more likely to be a problem when fruit is allowed to fully ripen on the plant and when poor sanitary conditions are found on field bins and at the packinghouse. This study determines the feasibility of detecting *R. stolonifer* conidia at the tomato surface of red mature fruits using optical reflectance. Spectral measurements of inoculated and spore free tomatoes were acquired with a radiometer and/or with a spectrometer which was programmed to acquire the desired wavebands. Discriminant algorithms used the spectral

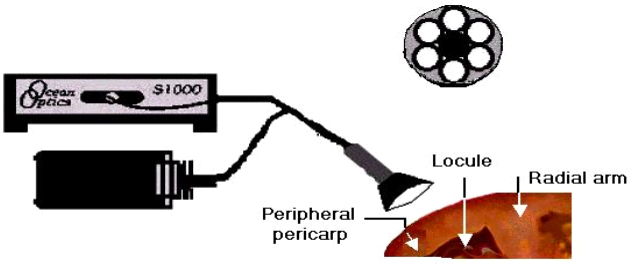

Fig. 1. Cone at the optical fiber end for measuring spectral reflectance.

measurements to predict whether the tomato was infected or spore free. The study was carried out using variable bandwidths and it was fiund that 1 nm wavebands worked best achieving an average success rate over 90%. The radiometer using 10 nm width filters presented lower success rates. Tomatoes inoculated with four different concentrations were sampled on-line and a threshold logic was used obtaining a detection accuracy of 92% for a concentration of 6.5 x 10^4 sporangiospores/mL. The variable threshold results are encouraging and could increase the discriminant accuracy even higher.

MATERIALS and METHODS

Tomato spectral sampling

Two hundred red tomatoes were collected from a packinghouse and were carefully washed with clean water to remove dirt and pathogens from the tomato surface. Red tomatoes were selected to avoid spectral changes caused by maturation during the analysis. The tomatoes were enumerated and a circle line having a diameter of 25 mm was marked on each tomato equatorial region. An Ocean Optic PC 1000 (Ocean Optics, Dunedin, FL) computerized spectrophotometer was used to acquire spectral reflectance signatures in the 500-1000 nm range. The Ocean Optic monochromator grating provided reflectance values every 0.5 nm. Ten consecutive spectral bands were averaged to obtain a 5 nm waveband.

The spectral measurements over the tomato tissue were obtained with a bifurcated optical fiber, which carried the illuminating radiation towards the produce and the reflectance back to the monochromator. A cone adapted to the fiber probe end, measured the tomato surface reflectance at a height of 10 mm, avoiding direct contact with the conidia as shown in Fig. 1. The maximum signature reference was obtained by irradiating the Spectralon material with the spectrophotometer halogen light source, while the minimum or dark signature reference was obtained with the spectrophotometer light source off. Spectralon diffuse reflectance material (Labsphere Inc., North Sutton, NH) was used as the spectral reference due to its high reflectivity (98 - 99 %) in the 250 - 2500 nm range. Both references were acquired at the beginning of the experiment and periodically after sampling 20 tomatoes. The relative reflectance (RR) was evaluated by dividing the difference between the tomato reflectance signature (TR) and the dark reference spectrum (DR) against the difference between the Spectralon (SR) and dark reference spectrum:

$$RR(\%) = \frac{TR - DR}{SR - DR} \qquad (1)$$

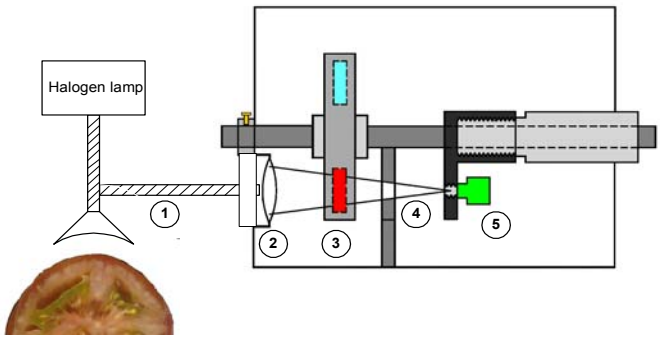

Fig. 2. Fiber probe (1), condenser lens (2), filter wheel (3), shutter (4), and photodetector (5) of the radiometer built for measuring the spectral bands.

Red colored tomatoes present similar spectral signatures due to lycopene synthesis and lack of chlorophyll content. The red tomato spectral signatures are very similar and those acquired before inoculation on the laboratory experiment were averaged to obtain the relative reflectance signature RTR. A program developed in C++ acquired the selected wavebands with the spectrophotometer directly (Hahn 2001).

Tomato inoculation *Rhizopus stolonifer* sporangiospores obtained from rot tomatoes were added to sterilized distilled water and mixed. A 50 µL drop of water containing 6.5 x 10^4 sporangiospores/mL (determined with a hemacytometer) was applied with a pipette within the mark of one hundred tomatoes. A 50 µL drop of sterilized distilled water without conidia was applied to the other one hundred tomatoes. Twenty minutes later, the relative reflectance (TR20) on the same tomato site was acquired, once the water containing the fungal spores dried. The conidia relative reflectance CR was obtained by subtracting the relative reflectance acquired before inoculating (RTR) from the relative reflectance after inoculating (TR20). This value should be 0 if the tomato was not infected.

$$CR = TR20 - RTR \qquad (2)$$

Radiometer construction The radiometer using the spectrometer fiber probe with the cone on one end collected the radiation by means of a condenser lens and directed it towards a photodetector (Fig. 2). The silicon S1336-18BU photodetector (Hamamatsu Photonics UK, Welwyn Garden City, Hertfordshire, UK) provided a value proportional to the incoming radiation, which was maximized by moving the photodetector until it was properly focused. The radiometer was capable of measuring up to six different reflectance bands using filters which were rotated manually.

With the filter wheel fixed on the first position, the trigger opened the shutter and the acquired reflectance measurement was converted to digital and sent via the parallel port to the computer. The voltage measured at the photodetector amplifier output decreased to a minimum when the shutter closed, when the filter wheel was ready to be rotated to the next position. The photodetector dark reference was measured and the radiometer was ready to sample again. The five 10 nm band pass filters used to detect *Rhizopus sp.* infected tomatoes with the radiometer were 630, 660, 690, 740 and 770 nm (EALING 35-3862, 35-4001, 35-4084, 35-4241 and 35-4324). A 745 nm commercial filter was not available so a 740 nm filter was

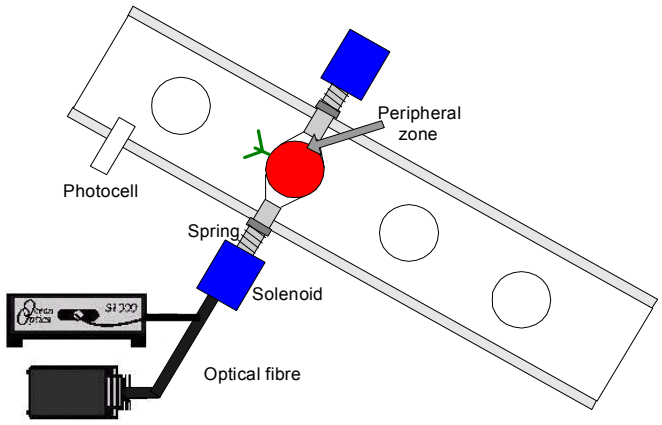

Fig. 3. On-line conveyor.

selected, as its average reflectance was closer to the R745 value than the reflectance value provided by the 750 nm filter. In the case of R625, a 630 nm filter was selected for measuring the R625 variable as its average reflectance was closer to the 625 nm value. The 630 and 690 nm bandpass filters having a 10 nm bandwidth were interchanged by 1 nm band pass filters at 632.8 and 694.3 nm (Ealing 35-8630 and 35-8762).

Conveyor belt design

A conveyor belt was designed in order to measure automatically the spectral signature on the tomato inoculated area. A leather conveyor belt having holes with a diameter of 70 mm transported the tomatoes avoiding rolling (Fig. 3). The conveyor belt, which had two consecutive holes, every 150 mm rotated at 34 RPM being moved by a gearmotor (Mod. NC154RL, Bodine Electric, Co., Chicago, IL).

The spectral measurements taken over the tomato tissue were obtained with the bifurcated optical fiber of the Ocean Optic PC 1000 computerized spectrophotometer working on the 500-900 nm range and providing reflectance values every 0.5 nm. A pair of solenoids placed one in front of the other grabbed the tomato for sampling. The fiber probe was fixed to the center of the solenoid tubular mechanism as shown in Fig. 3. A cone on its extreme limited external radiation. Four different concentrations (7.3×10^4, 6.5×10^4, 5.6×10^4 and 4.2×10^4 sporangiospores/mL) determined with a hemacytometer were applied to four groups of one hundred tomatoes each. A 50 µL drop of sterilized distilled water without conidia was applied to the other one hundred tomatoes.

A control board based on the ATMEL 89C51 microcontroller was designed to fire the solenoids precisely for sampling the tomato infected zone. A photoelectric sensor (Mod. MF01AD4, Infra SRL, Vicenza, Italy) was used to detect the fruit size by measuring the time it reflected the emitted light. The microcontroller provided the signals for firing a pair of triacs, which actuated the solenoids during 0.1 seconds. The spectral signature acquired from each tomato was sent to a Pentium IV HP Brio PC for analysis. The solenoids were fired a period T after the photodetector finished counting. The period consisted of a constant value of 0.42 seconds that corresponded to the time required by the belt to advance the distance of 15×10^{-2} m encountered between holes (Fig. 3) and the tomato size provided by the photodetector count.

Statistical analysis

The two ratio signatures obtained by tomato (before and after inoculation) were subtracted and analyzed by discriminant analysis using the North Carolina Statistical Software (NCSS). Discriminant analysis trained an algorithm to classify the tomatoes as infected or spore-free. Of the 200 spectra acquired for detecting the presence of *R. stolonifer* conidia, 140 were used to train the classifier and 60 as a trial group. The success of a particular program defining wavelengths was determined by the success in classifying a case from the trial group into its correct category of spore-free or infected. The effect on the detection accuracy caused by the spectral bandwidth was studied using 1, 2, and 5 nm bands. The signatures acquired by the spectrophotometer were made 2 and 5 nm wide after averaging 4 and 10 consecutive measurements.

One hundred tomatoes were infected with each spore concentration. The four hundred infected tomatoes and the one hundred spore free tomatoes were then sampled on the conveyor belt with the spectrophotometer programmed to acquire the 1 nm wavebands of Eqs. 5 and 6. A tomato was considered spore-free when the output value obtained from Eq. 5 exceeded 0.5, while an infected one required a value over 0.5 on Eq. 6.

RESULTS and DISCUSSION

Tomato spectral signatures

As reflectance ratios are not affected by lightning differences, tomato signatures were rationed against one of the two reflectance peaks at 630 or at 745 nm (Hahn 1998). The spectral signature measured at the tomato surface was affected by the fruit anatomy (Fig. 1). Measurements taken over the radial arms of the pericarp, which impart resistance to the fruit, presented high reflectance (Barrett et al. 1998). A lower reflectance was obtained when the tomato peripheral pericarp was sampled. This zone covers the locular cavities and is characterised by cells with thin walls and separated by many intercellular spaces (Grierson and Kader 1986).

The average relative reflectance at 745 nm obtained from measurements taken over the peripheral and radial arms of the pericarp were of 39.81 ± 6% and 51.42 ± 6%, respectively. Reflectance ratio measurements reduced the spectral difference between the radial arm and peripheral pericarp from 34.8% to 4.1% at 745 nm. Two hundred spectral signatures were acquired from infected and spore free tomatoes at the peripheral pericarp. The higher spectral difference between inoculated and non-inoculated signatures was noted in the 600-700 nm range, and no substantial differences were present above 700 nm (Fig. 4).

Best wavelength selection for *R. stolonifer* conidia detection

More than seven hundred program runs were carried out using the NCSS software, to determine the best discriminant wavelengths with the relative conidia spectra rationed against 630 and 745 nm. From Table 1, the best discriminant wavelengths for detecting the presence of *Rhizopus sp.* conidia in tomatoes were 625-630, 660, and 690-695 nm. Program run 430 showed a 79.16% success rate in detecting *R. stolonifer* with only four wavelengths. The average success rate increased to 82.62% in program run 453, with the best discriminant wavelength at 625 nm. Prediction of tomatoes free of conidia was 87.18% accurate. Program run 453 discriminant Eqs. 3 and 4 are:

$$Spore-free = \frac{341.84(R625)}{R745} + \frac{827.26(R660)}{R745} - \frac{214.6(R690)}{R745} + \frac{1882.4(R770)}{R745} - 1499.36 \quad (3)$$

$$Infected = \frac{319.26(R625)}{R745} + \frac{784.01(R660)}{R745} - \frac{180.19(R690)}{R745} + \frac{1915.58(R770)}{R745} - 1489.61 \quad (4)$$

The R before the wavelength number on the variables indicates that the spectral band is 5 nm wide.

Band width effect on accuracy An analysis was carried out to determine the effect of bandwidth on detection accuracy. The signatures acquired by the spectrophotometer were made 1 nm and 2 nm wide after averaging 2 and 4 consecutive measurements. The number of variables (500) was too big for the NCSS program, so only the 600-810 nm waveband was analyzed. This waveband covered most of the wavelengths shown on Table 1. Three hundred discriminant program runs were carried out using the relative conidia spectral signatures rationed against 630 and 745 nm presenting reflectance values 1 or 2 nm wide. The highest accuracy of 91.47% for detecting spore free tomatoes was achieved on program run 748 with the best discriminant wavelengths being 632, 667, 694, and 775 nm (Table 2). It can be noted that the wavebands are a little bit higher than the ones of program run 453. Program run 748 discriminant Eqs. 5 and 6 show a RE character before the wavelength variable indicating that they are 1 nm wide:

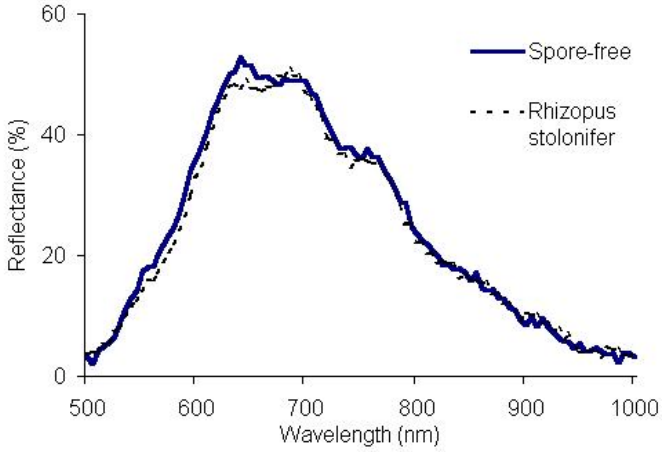

Fig. 4. Average spectral signatures of spore free and R. stolonifer infected tomato taken over the peripheral pericarp.

Table 1. Success rates for detecting tomatoes with localized *R. stolonifer* inoculation.

Program No.	Best wavelengths (nm)	Ratio wavelength (nm)	Discriminant accuracy (%)		
			Non inoculated	Inoculated	Average
420	630, 660, 695, 890	745	75.00	77.08	76.04
430	630, 660, 695	745	77.08	79.16	78.12
614	660, 695, 775	630	83.33	75.00	79.17
453	625, 660, 690, 770	745	87.18	78.05	82.62
634	685, 730, 805, 885	630	84.62	84.62	84.62
642	570, 685, 730, 750	630	82.05	82.05	82.05

Table 2. Success rates for detecting tomatoes with localized *R. stolonifer* inoculation using 1 and 2 nm spectral bandwidths (BW).

Program No.	BW (nm)	Best wavelengths (nm)	Ratio wavelength (nm)	Discriminant accuracy (%)		
				Non inoculated	Inoculated	Average
748	1	632, 667, 694, 775	745	91.47	88.92	90.19
814	2	632, 666, 694, 776	744	90.32	87.18	88.75
752	1	632, 667, 775	745	88.92	86.42	87.67
867	1	664, 692, 751, 774	630	88.92	84.62	86.77
453	5	625, 660, 690, 770	745	87.18	78.05	82.62

$$Spore-free = \frac{224.83(RE632)}{RE745} + \frac{223.14(RE667)}{RE745} - \frac{344.98(RE694)}{RE745} + \frac{1124.33(RE775)}{RE745} - 989.36 \quad (5)$$

$$Infected = \frac{688.14(RE632)}{RE745} + \frac{182.14(RE667)}{RE745} - \frac{139.19(RE694)}{RE745} + \frac{1915.58(RE775)}{RE745} - 1489.61 \quad (6)$$

Program run 867 presented a high 84.62% detection accuracy on infected tomatoes, using 1 nm wide tomato reflectance values

Table 3. Discriminant accuracy for detecting *R. stolonifer* conidia using the radiometer and the spectrophotometer.

Equipment	BW (nm)	Wavelengths (nm)	Discriminant accuracy (%)		
			Non inoculated	Inoculated	Average
Spectrometer	10	625, 660, 690, 745, 770	80	78	79
Radiometer	10	630, 660, 690, 740, 770	75	73	74
Radiometer	10/1	632, 660, 694, 745, 770	76	76	76
Spectrometer	5	625, 660, 690, 745, 770	85	78	81.5
Spectrometer	2	632, 666, 694, 744, 776	88	87	87.5
Spectrometer	1	632, 667, 692, 745, 775	90	87	88.5

Table 4. Success rates for detecting inoculated tomatoes with variable *R. stolonifer* concentration 20 minutes after inoculated and on hour later.

Concentration (sporangio spores/mL)	Discriminant accuracy (%)			Discriminant accuracy (%) one hour later		
	Spore-free	Inoculated	Average	Spore-free	Inoculated	Average
7.3×10^4	85	89	87	85	74	79.5
6.5×10^4	85	87	86	86	76	80
5.6×10^4	85	86	85.5	85	69	77
4.2×10^4	85	73	79	83	63	73

rationed against 630 nm. The best accuracy using reflectance spectral bandwidths of 2 nm was achieved by program run 814, being infected and spore free tomatoes classified with success rates of 87.18 and 90.32%, respectively. Table 2 shows that the best discriminant wavebands of the signatures rationed against 744 nm were at 632, 666, 694, and 776 nm. Program runs 748 and 814 had in 632 nm the most important waveband. Accuracy detection increased as variable bandwidth decreased and was always better for detecting spore free tomatoes than infected tomatoes.

Radiometric measurements One hundred infected tomatoes and one hundred spore free tomatoes were sampled with the radiometer. Equations 3 and 4 were calculated using the conidia relative reflectance values and provided as result a spore free or infected output value. Equation 3 analyzed one hundred non-infected tomatoes and 75% spore-free tomatoes were detected properly as shown on Table 3. Tomatoes were considered spore-free when the output value obtained from Eq. 3 exceeded 0.5. Conidia presence was successfully detected on 73% of the infected tomatoes when Eq. 4 exceeded a value of 0.5. Table 3 shows that infected tomato detection accuracy increased to 76% as the filter bandwidth was reduced.

On-line measurements

During the first test, the conveyor belt did not work properly as the tomatoes could not be grabbed by the solenoids. A ramp was added beneath the band just where the solenoids were located. Once the tomato was lifted from the hole the solenoids were able to grab the fruit. Nonetheless, moments before the solenoids were fired, the fruit was free to move. It was noted that in 55% of the cases the marked inoculated area did not remain in front of the sensing solenoid. Two options were implemented in order to avoid tomato movement. On the first option, a hole was made on the center of the base. On a hole having a diameter of 50 mm, 27% of the samples turned around, meanwhile with a diameter of 75 mm only 12% changed position. On the second option the ramp was displaced 50 mm to the right. With ramp displacement the tomato was lifted partially and maintained its proper position. It was adopted as it worked better than the hole option, which was size dependent.

Once the power was taken away from the solenoids after 0.1 second, the tomato did not fall over the hole again. A timing of 0.42 second was required so that the tomato fell exactly over the next hole. The tomatoes were fed manually with the infected mark on the right side. The solenoid compression spring was made of stainless steel having a diameter of 14 mm and a pitch of 7 mm. Four different wire gages were tested: 12, 13, 14, and 15. The spring of gage 15 was the best against tomato bruising, but it lost compression after 100 impacts, so the spring was built of gage 14. The conveyor belt could sample two tomatoes per second, but as the fruit was handled manually, only one fruit was sampled per minute. Springs of gage 12 caused bruising in 19% of the sampled tomatoes.

Probably the best contribution of the detection model was that only one measurement was required per tomato, making it possible for on-line measurement. Table 2 shows that from 100 non-infected tomatoes 85% were accurately detected using Eq. 5. Eighty seven of the one hundred infected tomatoes with 6.5×10^4 sporangiospores/mL were correctly classified (Table 4). The best discriminant accuracy was achieved for the higher concentration. The infected detection accuracy decreased to 73% on tomatoes inoculated with a concentration of 4.2×10^4 sporangiospores/mL. Inoculated tomato detection accuracy decreased when measurements were taken after one hour of being inoculated (Table 4).

Detection accuracy using threshold logic

Three threshold zones (0-0.3, 0.31-0.69, and 0.7-1) were implemented for each equation in order to cover the entire 0 to 1 output range. Instead of having one equation for predicting spore free tomatoes and another for calculating infected tomatoes, the variable threshold logic used a combination of both equations to forecast whether the tomato was infected. If the results of Eqs. 5 and 6 were within given thresholds the tomato was considered infected.

Table 5 shows the infected tomato detection accuracy using threshold logic. Infected tomatoes with an infection concentration of 6.5×10^4 sporangiospores/mL were detected with a 92% success rate when the output value from Eq. 6 was over 0.3 and when the result from Eq. 5 was less than 0.3. Lower success rates were obtained with band thresholds ranging within 0 and 0.3 on Eqs. 5 and 6 and only 28 of 100 tomatoes

Table 5. Discriminant accuracy for detecting infected tomatoes using variable thresholds having infections of 6.5 x 10^4 and 5.6 x 10^4 sporangiospores/mL.

Threshold Eq. 5	Threshold Eq. 6	Discriminant accuracy (%)	
		6.5 x 10^4 sporangiospores/mL	5.6 x 10^4 sporangiospores/mL
0-0.3	0.31-0.69 and 0.7-1	92	91
0.31-0.69 and 0.7-1	0-0.3	89	90
0.31-0.69 and 0.7-1	0.31-0.69 and 0.7-1	88	86
0.31-0.69	0.31-0.69	42	40
0.7-1	0.7-1	36	39
0-0.3	0-0.3	28	28

were properly identified. Similar results were achieved using an infected concentration of 5.6 x 10^4 sporangiospores /mL. The use of two discriminant equations provides a 2-dimensional environment. Threshold levels can have "n x m" possibilities, so a program should be implemented to analyze iteratively the data for providing the optimum response, using narrower threshold bands.

CONCLUSIONS

This paper shows that *R. stolonifer* conidia can be detected in red tomatoes. The following conclusions were obtained from this work:

1. Accurate detection is bandwidth dependent, with non-inoculated accuracies always higher than inoculated ones.
2. A radiometer is not practical for use on spore detection as narrow band pass filters are difficult to get.
3. It is necessary to be careful during the second spectral measurement as all the water of the inoculum had to be gone.
4. *R. stolonifer* conidia can be detected on-line.
5. The solenoid compression spring was critical and should be designed to avoid bruising.
6. It is necessary to present the tomatoes in front of the solenoids properly.
7. Only one measurement per tomato was required for on-line measurement.
8. As the inoculated spores decreased, the efficiency was reduced, because the reflectance value of the tomato surface became lower.
9. The spores after one hour were not the same as at the start and the detection accuracy decreased.
10. The use of threshold logic increased the detection accuracy.

In the future, work should be done with tomatoes under different maturity stages and with spores all around the surface. Although this has been the first effort on detecting infections on-line, the place of infection was well known. A mechanism is now being tested which can see the entire surface. Rolling mechanisms are not very good as a contaminated fruit can leave spores on the band and another tomato could get them.

REFERENCES

Agrios, G.N. 1988. *Plant Pathology*. New York, NY: Academic Press, Inc.

Aneshansley, D.J., J.A. Throop and B.L.Upchurch. 1997. Reflectance spectra of surface defects on apples. In *Proceedings of Sensors for Nondestructive Testing: Measuring the Quality of Fresh Fruits and Vegetables*, 143-160. Publication NRAES -97. Ithaca, NY: Cooperative Extension, Northeast Regional Agricultural Extension Service, Cornell University.

Armendáriz, A. 1997. Se produciran cerca de dos millones de Ton de tomate. [Two million tones of tomato will be produced.] Hortaliza, Frutas y Flores. October 1997, pp 14-18.

Barrett, D.M., E. Garcia and J.E. Wayne. 1998. Textural modification of processing tomatoes. *CRC Critical Reviews in Food Science and Nutrition* 38(3): 173-258.

Boyette M.D., D.F. Ritchie, S.J. Carballo, S.M. Blankenship and D.C. Sanders. 1994. *Chlorination and Posharvest Disease Control*. Publication AG-414-6. Raleigh, NC: North Carolina Cooperative Extension Service.

Cadwell, D.E. and J.R. Lawrence. 1989. Image analysis and computer modeling of microbial growth on surfaces. *Binary* 1: 147-150.

Ceponis M.J. and J.E. Butterfield. 1979. Losses in fresh tomatoes at the retail and consumer levels in the Greater New York Area. *Journal American Society of Horticultural Science* 104: 751-754.

Dowell, F.E., M.S. Ram, N. Zhang, T.J. Herman and L.M. Seitz. 1998. Detection of scab in single wheat kernels using NIR spectroscopy. ASAE Paper No. 983062. St. Joseph, MI: ASAE.

Goodacre, R. and D.B. Kell. 1996. Pyrolysis mass spectrometry and its application in biotechnology. *Current Opinion Biotechnology* 7: 20-28.

Grierson, D. and A.A. Kader. 1986. Fruit ripening and quality. In *The Tomato Crop: A Scientific Bases for Improvement*, eds. J.G. Atherton J. and Rudich, 241-280. London, UK: Chapman and Hall.

Hahn, F. 1998. Tomato maturity prediction using optical reflectance. ASAE Paper No. 983065. St. Joseph, MI: ASAE.

Hahn, F. 2001. Tomato maturity detection and its correlated diseases. Final Technical Report. CIAD Unidad Culiacán, México (In Spanish).

Hahn, F. 2002. Fungal spore detection on tomatoes using spectral Fourier signatures. *Journal of Biosystems Engineering* 81: 249-259.

Lanza, E. and B.W. Li. 1984. Applications of near infrared spectroscopy for detecting the sugar content of fruit juices. *Journal of Food Science* 49: 995-998.

Morgan, P., C.J. Cooper, N.S. Battersby, S.A. Lee, S.T. Lewis, T.M. Machin, S.C. Graham and R.J. Watkinson. 1991. Automated image analysis method to determine fungal biomass in soils and solid matrices. *Soil Biology Biochemistry* 23: 609-616.

Sommer, N.F. 1982. Posharvest handling practices and postharvest disease of fruit. *Plant Disease* 66: 357-364.

USDA. 1991. United States Standards for Grades of Fresh Tomatoes. Washington, DC: USDA, Marketing Services.