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Optimal laser marking of 2D data matrix codes on Cavendish bananas

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Abstract

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A traceability system is an effective tool to guarantee safety in horticultural products and to improve supply chain transparency. A direct data matrix (DM) code created with carbon dioxide laser (wavelength 10.6 μm) can be used as a trust mark on bananas. In this study, green bananas were marked with the above-mentioned CO_2 laser. Subsequently, the samples were held under storage conditions. Images of the codes on bananas were captured by using two different cameras; i.e. hyperspectral imaging camera and charge-couple device (CCD) camera. Image processing was used for evaluating print quality of 2D codes based on the ISO/IEC 15415 standard. The quality of the codes on bananas mainly depends on some parameters: laser power, laser energy, marking time per module and storage time. The best readability results were achieved by using laser power of 1.8 W and marking time of 0.09 s per data matrix module, whereby an 80–100% readability of DM codes after the storage was obtained.

Keywords: traceability; CO_2 laser; image processing; readability

Due to globalization in food trade, consumers are looking for trust marks on agricultural products. Moreover, consumers also demand verifiable evidence of traceability, not only regarding safety concerns but also in terms of protection against fraud. Traceability contributes to increasing consumer confidence and plays an important tool in establishing the authenticity of the food (Verbeke et al. 2007; Van Rijswijk et al. 2008). Recent developments in traceability technologies include data handling systems based upon radio frequency identification (RFID), wireless sensor networks (WSN) and barcodes. While RFID and WSN are promising techniques, they remain relatively high in cost (Michael, Mccathie 2005; Hong et al. 2011; Lin et al. 2011; Ruiz-Garcia et al. 2011; Parreño-Marchante et al. 2014). By contrast, barcodes are relatively inexpensive and widely used in traceability systems (Marx et al. 2013). Two-dimensional barcode (data matrix code) was selected for this study, due to high readability of distorted codes and the small size of the symbol. Numbers and characters are encoded in terms of bits, represented by dark or light modules of an identical size. The larger the amount of bits required, the larger the symbol will be, but it increases the density of modules in the code. A DM code is surrounded by an "L finder pattern", which is surrounded by a quiet zone area on all four sides of the symbol (Fig. 1). Two opposite sides known as "clock track" comprise alternating dark and white modules (GS1 2014).

Applications of label-based marking have been developed for fruit and vegetables. However, adhesive labels on fresh fruits and vegetables have several disadvantages, including that the labels can easily be detached, lost or exchanged (Drouillard, Kanner 1999; Etxeberria et al. 2006; Marx

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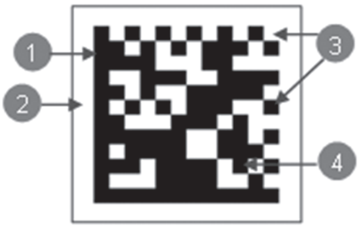

Fig. 1. Data matrix structure

et al. 2013). Researchers have recently shown an increased interest in laser marking of fruits, flowers, plants, eggshells, chicken beaks, wood or vegetables (Drouillard, Kanner 1999; Jones et al. 2001; Chitu et al. 2003; Etxeberria et al. 2006, 2009; Sood et al. 2008, 2009; Chen et al. 2009; Danyluk et al. 2010, 2013; Mc Inerney et al. 2011a;b; Marx et al. 2013). There are several advantages of using laser labelling compared to conventional labelling, e.g. a permanent, higher quality mark, higher marking speed and higher reproducibility. Most of the laser markings on agricultural products use alphanumeric codes to indicate the date of production, origin, etc. However, there has been little discussion about the use of 2D barcodes (i.e. DM codes) in food production to date. Only Fröschle et al. (2009) reported an application of 2D barcode traceability for individual animals at poultry farms. This study aims at developing a 2D barcode system for food product traceability, which could be applied on fruits and vegetables.

At present, each banana that enters into a conventional product chain is labelled with a paper sticker. The present work develops distinguishable 2D barcode marks on banana surfaces due to depigmentation processes caused by a CO_2 laser beam. However, the application of the DM code directly on the surface of a product by a laser labelling system can affect cell damage in the epidermis area, tissue becomes browned and even applying higher laser power will produce carbonization in the marked area. Drouillard and Kanner (1999) recommended that the depth of the mark should not exceed one cell of skin thickness to prevent thermal degradation and breakdown of the underlying tissue. Since damage on the cuticular barrier influences the readability of the code, optimal laser marking parameters should be applied. Moreover, it is essential to ensure easy reading of the codes. The aim of this research is thus to investigate the application of laser DM codes on Cavendish bananas by determining the optimal laser marking systems (laser power, laser energy, marking time per module and storage time).

MATERIAL AND METHODS

Bananas preparation. Mature green bananas (*Musa spp.*, Cavendish subgroup) were acquired from Dole® Fresh Fruit Company, Stelle, Germany. Samples with visual defects were removed. Banana fingers were separated from banana hands and marked by using a CO_2 laser (wavelength: 10,600 nm, type 48–5, Synrad Inc., USA). The samples were treated for 24 h with ethylene at 1,000 ppm and stored at 16.6°C (relative humidity (RH) 80%) to initiate ripening. Subsequently, the bananas were held under storage conditions for five days in a ripening chamber to reach yellow bananas, and then stored again in room temperature (20°C) for four days to simulate a banana supply chain from the ripening room to the market.

Laser marking setup. A CO_2 laser (continuous wave) produced DM codes on bananas. The distance from the laser scanning system (marking head SH3-200C, galvanometer-operated mirrors, Synrad Inc., USA) to the fruit surface was set to 246 mm (flat-field lens). In order to always ensure the same distance from the object surface to the laser scanner focus system, an automatic banana lifting machine was developed (Fig. 2). The machine comprises a stepper motor, three laser diodes and three photodiode sensors. The diode system was

Table 1. Laser energy (Joule per module) applied to bananas depending on the laser power and marking time

Laser power (Watt)	Marking time (s per module)			
	t1 (0.0937)	t2 (0.0724)	t3 (0.0537)	t4 (0.0381)
p1 (2.2)	p1t1 (0.206)	p1t2 (0.159)	p1t3 (0.118)	p1t4 (0.084)
p2 (2.0)	p2t1 (0.187)	p2t2 (0.145)	p2t3 (0.107)	p2t4 (0.076)
p3 (1.8)	p3t1 (0.169)	p3t2 (0.130)	p3t3 (0.097)	p3t4 (0.068)
p4 (1.6)	p4t1 (0.150)	p4t2 (0.116)	p4t3 (0.086)	p4t4 (0.061)

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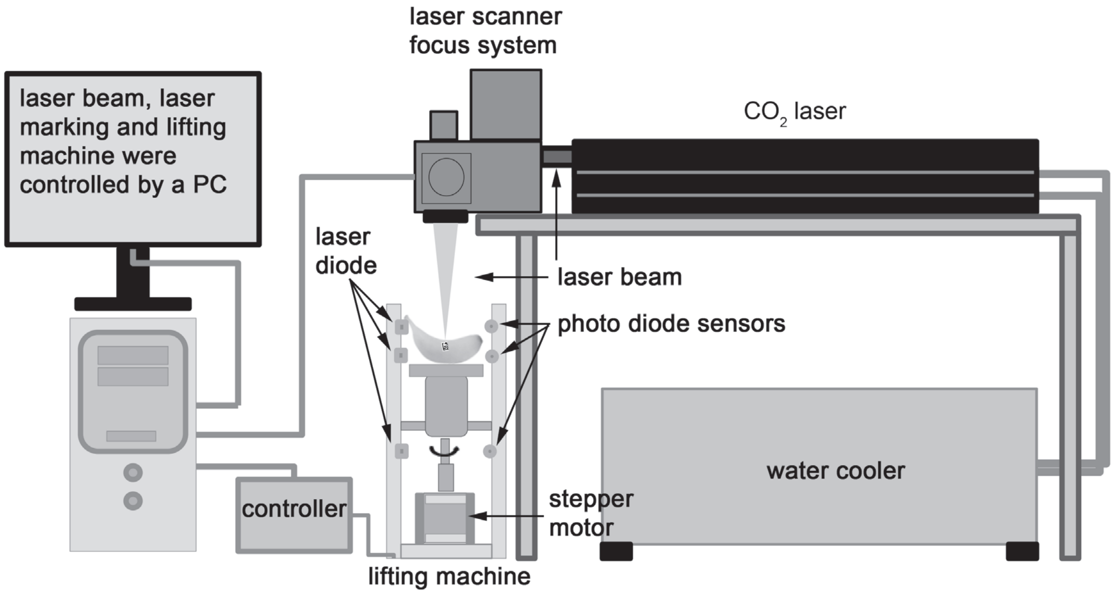

Fig. 2. Laser marking setup: CO_2 laser, laser scanner and focus system, banana lifting machine and computer-based control

used to steer the lifting machine to the exact right banana-laser distance by sending a signal to the stepper motor to move up and down.

Laser marking parameters. The modules of the DM codes were created with energy inputs, laser powers and marking times shown in Table 1. The treatments were selected from four levels of low-power laser in order to cause minimum damage to the banana peels. Various levels of marking times were referred to contrast values that can be stably decoded. The pattern size (edge length) was selected 10 mm due to the diameter of the bananas and their curvature. Overall, 16 different treatments with five replications were conducted. The DM code images were evaluated based upon the ISO/IEC 15415 standard. In order to decode and assess a DM code in an image, some general image processing steps in the Halcon software (MVTec Software GmbH, Munich, Germany) were used (Fig. 3). Table 2 provides information concerning how the parameters in step 6 in Fig. 3 have to be used in the ISO/IEC 15415 to grade DM codes.

Hyperspectral camera. Ripe bananas were marked with different laser powers (Fig. 4). The laser marking speed was fixed to 400 mm/s. Images were captured using a hyperspectral imaging camera (Helios, EVK DI Kerschhaggl GmbH Austria). The camera has 240 × 240 pixels with a spectral resolution of 2 nm and a spectral range from 1,100 nm to 1,700 nm. The acquired images were corrected with white and dark reference. The corrected image (I_c) is estimated as follows:

$$I_c = \frac{I_h - I_d}{I_w - I_d} \quad (1)$$

where: I_h – acquired hyperspectral image; I_d – the dark image recorded by closing the camera lens completely; I_w – white reference image with 99% reflectance using a Teflon white board

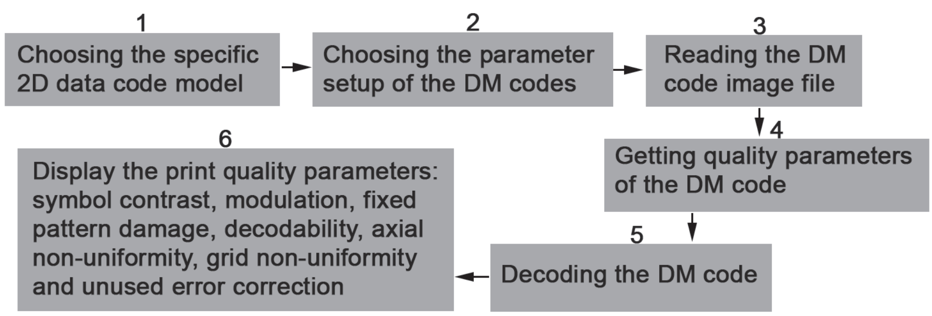

Fig. 3. Image processing steps to evaluate the data matrix codes by using the Halcon software

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Table 2. Summary of the data matrix code print quality (ISO/IEC 15415)

Parameter grade	Decode	Symbol contrast	Modulation	Fixed pattern damage	Axial non-uniformity	Grid non-uniformity	Unused error corection
4 (A)	passes	≥ 0.70	≥ 0.50	0%	≤ 0.06	≤ 0.38	≥ 0.62
3 (B)		≥ 0.55	≥ 0.40	≤ 9%	≤ 0.08	≤ 0.50	≥ 0.50
2 (C)		≥ 0.40	≥ 0.30	≤ 13%	≤ 0.10	≤ 0.63	≥ 0.37
1 (D)		≥ 0.20	≥ 0.20	≤ 17%	≤ 0.12	≤ 0.75	≥ 0.25
0 (F)	fails	0.20	< 0.20	> 17%	> 0.12	> 0.75	< 0.25

A – contrast: difference between minimal and maximal pixel intensity in the data code domain; B – fixed pattern damage: damage of fixed pattern or quiet zones; C – modulation: the uniformity of reflectance between light and dark elements; D – decoding or readability: determine whether the symbol (DM code) can be decoded or not. The percentage of readability (r) is calculated as follows: r = (k 100)/N, where k represents the number of read codes and N stands for the sample size; E – axial non-uniformity: the squareness of the symbol (distance between modules centre position is the same in horizontal and vertical directions); F – grid non-uniformity: the deviation of the modules from their ideal grid; G – unused error correction: the amount of error correcting capacities which is not already used by the present data code symbol

CCD camera. Images of marked bananas were captured with a CCD camera (DBK41BU02.H, The Imaging Source Europe GmbH, Bremen-Germany) equipped with a 4.5–12.5 mm lens (Computar H3Z4512CS-IR 1/2” varifocal day/night lens). All measurements were performed from the same distance and with controlled light conditions. The image acquisition was performed with the IC Capture ver. 2.0 TIS software (The Imaging Source Europe GmbH, Bremen-Germany).

RESULTS AND DISCUSSION

Spectral reflectance of the marked bananas

Fig. 5a compares the reflectance values of the five different areas in Fig. 4. Aside from using laser power of 2 W, the reflectance spectra in the near-infrared waveband of unmarked and marked bananas are almost identical (Fig. 5b). Considering these results, it would be not suitable to use near-infrared detection systems to analyse DM codes on bananas. Nevertheless, the reflection difference between marked and unmarked bananas in the visible waveband was noticeable. Especially at higher laser power, the banana skin becomes browner. According to ARIANA et al. (2006), reflectance of bruised tissue of cucumber fruit is generally lower than normal tissue. Bruised tissue on ‘Red Delicious’ apples also had lower reflectance than normal tissue (LU 2003). Various enzymatic or chemical reactions represent possible reasons for the colour change process in our banana experiments; accordingly, these factors would be an interesting area for future studies. Nonetheless, it shows very clearly that CCD cameras should be used in the visible waveband for analysing laser markings on bananas.

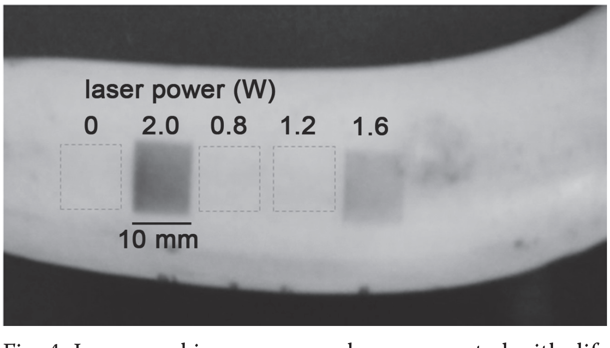

Fig. 4. Laser marking areas on a banana created with different laser powers

Data matrix qualities

DM codes with a laser power of 1.8 W and 1.6 W can be read constantly at longer marking times (0.094 s per module and 0.072 s per module) until 9 days of storage (data not shown), while a laser power of 2.0 W provides slightly better results at a shorter marking time (0.035 s per module). A laser power of 2.2 W in all marking time treatments demonstrates reduced readability after six days of storage (Fig. 6). The same laser energy

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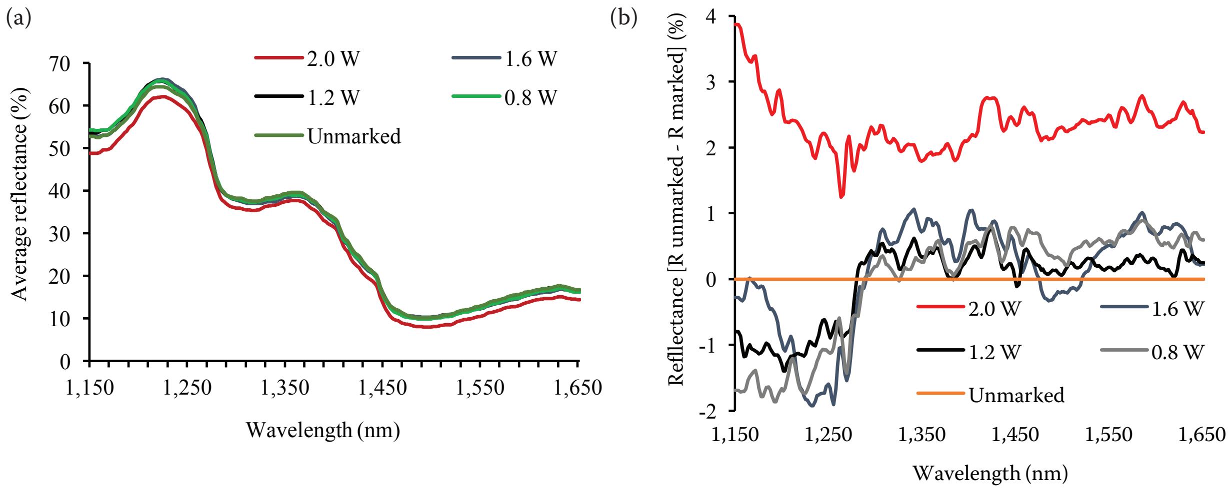

Fig. 5. Reflectance spectrum (R) of marked bananas in the infrared waveband (n = 10): (a) mean reflectance (b) reflectance difference

does not guarantee producing a high readability of the code; rather, it depends on the marking time. This fact is shown by the circle in Fig. 7, where similar energy leads to different code qualities. The appearance of darker colour areas in the DM modules and distortions in the finder pattern of the codes (Fig. 7) show that some damage occurred on the banana peel. The damage could be explained by a physiological mechanism due to wound reactions like browning, natural healing or repair response on outer cells during the storage period. Laser marking on the banana led to the breaking of epidermis cells and consequently to darkening of areas around the affected location. Marx et

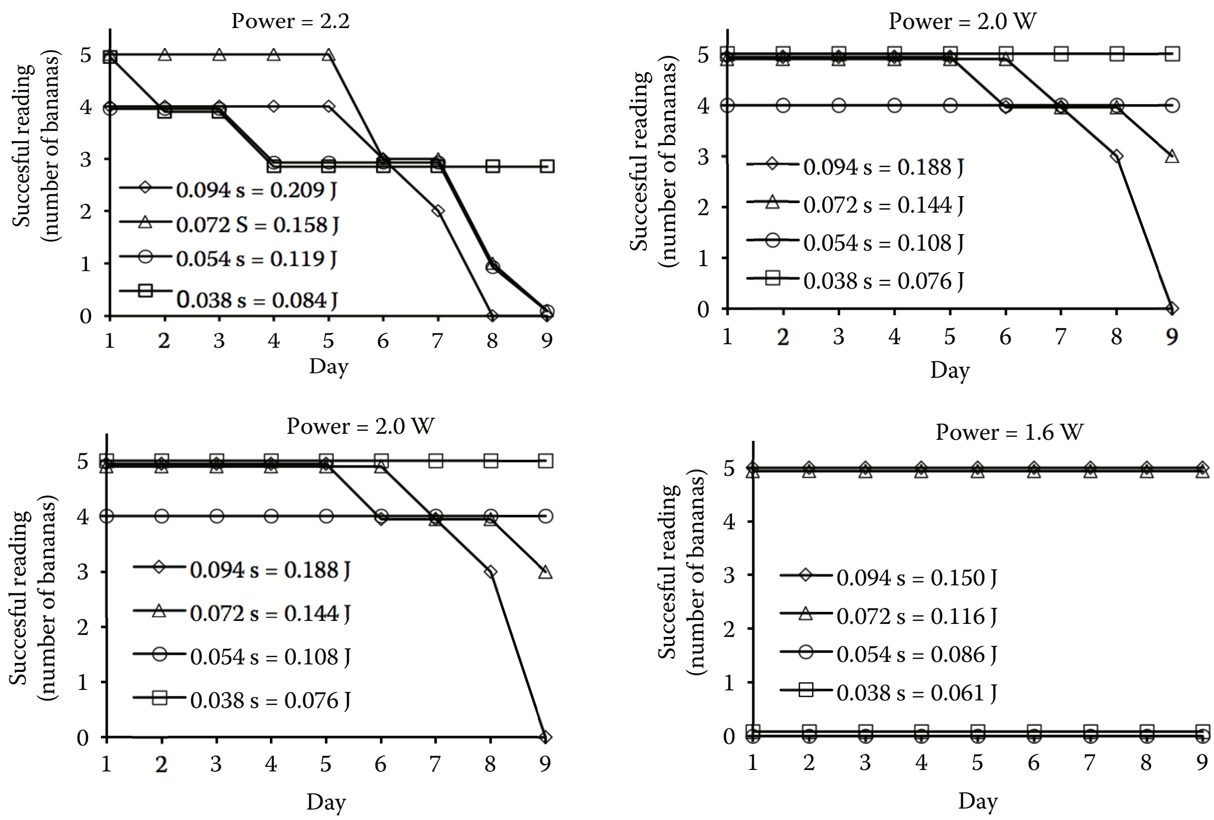

Fig. 6. Successful readings of the data matrix code on 5 bananas depending on the laser power (W), the marking time (s per module) and the storage time (day)

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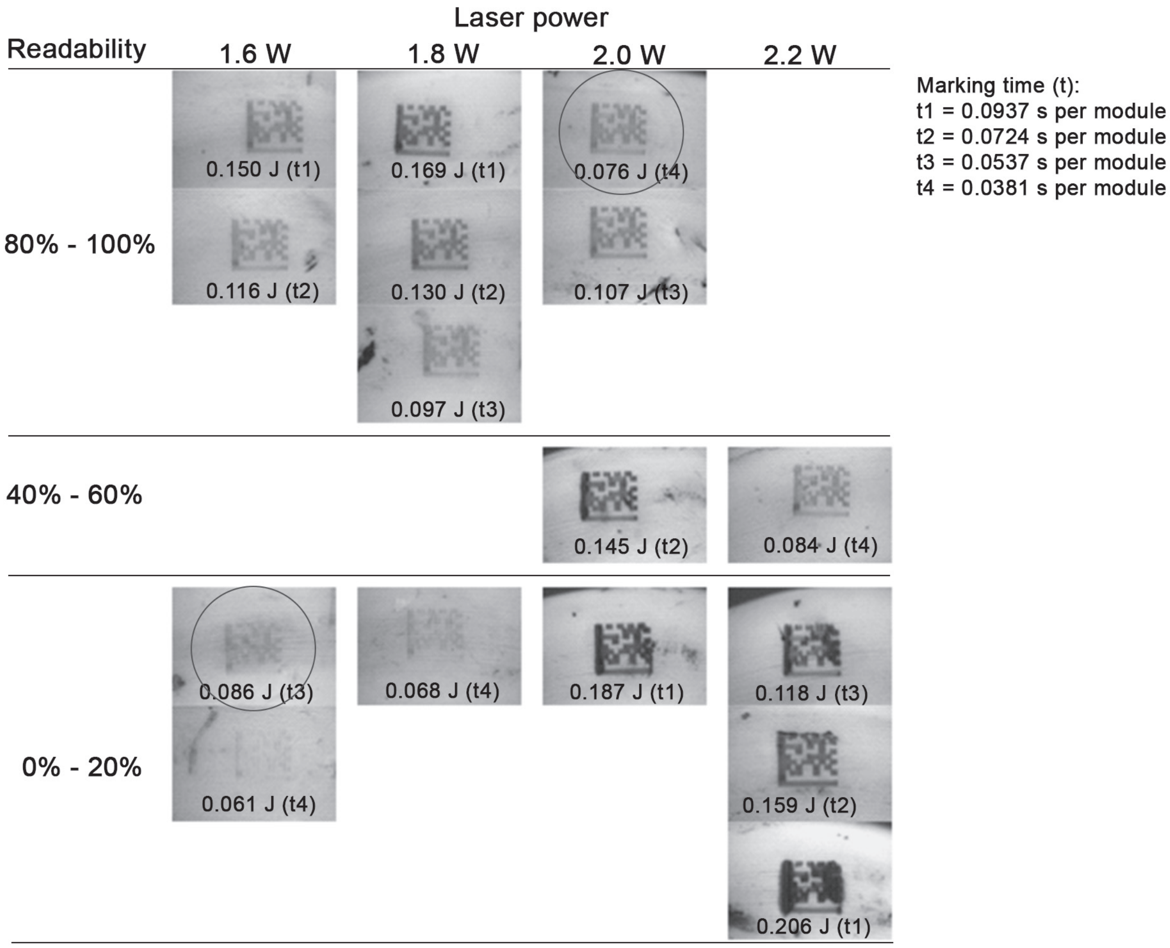

Fig. 7. Data matrix codes on bananas after 9 days of storage (data matrix edge length 10 mm, 10 × 10 modules)

al. (2013) described that tissue damage after laser marking can be explained by three different approaches: (1) browning happens due to oxidation processes in the marked area; (2) colour changes result from vaporizing the plant tissue; and (3) tissue of the marked area becomes burning, which leads to deep engraving. Etxeberria et al. (2006) reported a natural healing process in pinhole depressions by accumulating cutin and wax deposits in and around the depression after the laser marking of tomatoes and avocados. Buron-Moles et al. (2014) described that the increased abundance of proteins after wounding of 'Golden Delicious' apples is due to "response to stress". Fig. 8 shows that the combination of the laser power and marking time is directly proportional to the contrast. The optimal combination of both the laser power and the marking time becomes a key factor for producing high contrasts in the codes. It shows also that the contrast values increase after storage. There is no evidence that axial non-uniformity (ANU), grid non-uniformity (GNU) were influenced by the treatments and during the storage (data not shown). The two DM qualities of modulation and fixed pattern damage (FPD) could not be analysed because the results were zero. The high quality grade of both ANU and GNU are based upon a very well designed technical setup (Fig. 2). This is in accordance with well-known quality criteria of GS1 (2014). UEC values show no significant difference during the storage; these values are dominantly influenced by a small local deformation on the marked area over time. Sometimes this happened and could be seen on the peel, but overall this effect was not as important as the others.

Laser marking parameters

According to Table 3, the marking time has a significant positive correlation with the readability and the contrast value. The laser power only signifi-

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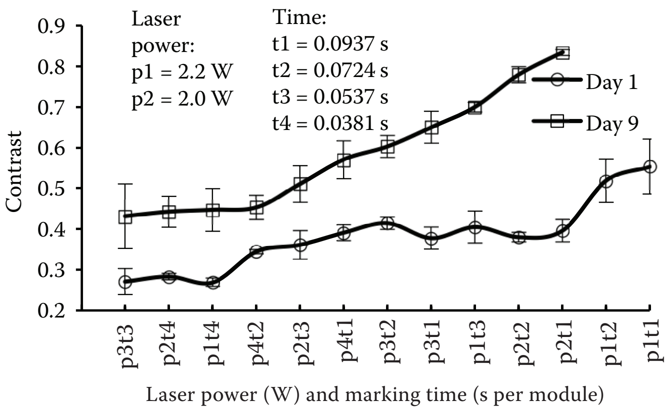

Fig. 8. Effect of combination of laser power and marking time on contrast values

cantly correlates with the contrast value, whereas no significant correlation is detected between the readability and the contrast value. Laser energy and marking time have positive correlations with readability of the code, while laser power gives no correlation. Accordingly, readability is more dependent on the laser energy and marking time than on the laser power. Marking at low laser energy for a short time tends to produce relatively low readability due to less contrast. However, applying low laser energy for a longer time will produce better readability. This behaviour was similarly described by Sood et al. (2008), namely that higher exposure time at a low laser energy level (0.000752 W/dot) creates darker labels without significantly increasing peel disruption on tangerines. By contrast, using high energy may potentially damage outer cell layers of bananas and promote unsuccessful readability of the codes. Once the laser beam has irradiated on the outer cells, photons penetrate into the epidermis layer and convert into thermal energy. Thus, the heat is distributed within the cells. According to Blanaru et al. (2003), the heat distribution is influenced by thermal properties, conductivity, heat capacity, convective coefficients and emissivity of the plant material.

Table 3. Correlation among the main variables of the study

Parameters	Correlation coefficient	
	contrast	readability
Laser energy	0.468***	0.397**
Laser power	0.278*	0.102
Marking time	0.329**	0.353**
Readability	0.122	

data were statistically analysed using the Spearman's correlation (n = 64); *p < 0.05; **p < 0.01; ***p < 0.001

Laser power and marking time have positive correlations with contrast values. Therefore, an optimal combination of the laser power and the marking time leads to higher contrast values. The more the laser energy is absorbed by banana, the higher is the contrast value. At the same time, the portion of the energy absorbed deforms the banana peel sufficiently to produce a visible mark. Jones et al. (2001) reported that different contrast levels on a leaf surface labelling may be adjusted to the level at which the mesophilic layer is sufficiently etched underside the epidermal layer by the laser beam.

CONCLUSION

The CCD camera is more suitable for detecting DM code on banana than the hyperspectral camera. Laser energy and marking time are suggested as useful parameters to ensure the best readability of DM codes on bananas. In addition, high code contrast values mainly depend on the laser power and the marking time. It is suggested that the use of laser power of 1.8 W and marking time of 0.09 s per module can be recommended for commercial use, because the obtained readability of the DM codes on bananas after nine days of storage was high (80%–100%).

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