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An evaluation of hyperspectral imaging for characterising milk powders

M.T. Munir [a,*], David I. Wilson [b], W. Yu [a], B.R. Young [a]

[a] Department of Chemical & Materials Engineering, Faculty of Engineering, The University of Auckland, Private Bag 92019, Auckland, New Zealand
[b] Engineering, Mathematics & Computer Science, Auckland University of Technology, New Zealand

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A B S T R A C T

The ability to quantify and qualify subtle differences between milk powders is very advantageous to industrial manufacturers. Hyperspectral imaging (HSI) combines the spatial attributes of image processing with the chemical diagnostic attributes of spectroscopy, and was evaluated to determine if it could be used to discriminate between milk powders produced in various factories, and of differing functional qualities, such as dispersibility. The results showed that HSI can achieve these aims when multivariate analysis techniques such as Principal Component Analysis (PCA) and Partial Least Squares (PLS) regression are applied. The PCA results showed that the most obvious differences were in the first and second principal components. Strategies to pre-process hyperspectral data, and to optimally automatically detect and remove artefacts in the images were also established. The PLS results showed that the information from HSI can be used to predict with reasonable accuracy the key functional property of dispersibility, and is the first step in a 'real-time quality' initiative to establish correlations between hyperspectral images and key quality attributes of milk powder either on, or at-line in close to real-time.

1. Introduction

Converting liquid milk into dry powder reduces the cost of transportation and extends shelf life. Powdered milk provides an alternative source of fat and protein for countries with limited domestic dairy farming or processing capabilities to meet their needs for liquid milk. In addition to reconstitution back to liquid milk, milk powder has many different uses such as an ingredient in foodstuffs such as baked and confectionery products, and even animal feed. However, these various uses of milk powder demand quite different functional characteristics and properties.

The physical properties of milk powder, such as bulk density, particle size distribution and powder structure, determine its storage and transport requirements. Functional properties, such as wettability, sinkability, dispersibility, solubility and heat stability, characterise how well the milk powder will perform when reconstituted with water (Sharma et al., 2012). Quantifying these properties, even following internationally established standards such as ISO/TS 17758:2014, is time-consuming, subjective, and currently performed post-manufacture. Consequently it is then possible that an industrial plant may produce significant amounts of off-specification powder prior to identifying a manufacturing problem (Rimpiläinen et al., 2015). Furthermore, some of these quality tests are highly discretised which has negative implications for any subsequent regression analyses.

On-line determination of the functional quality of milk powder is key to enabling 'Real Time Quality' (RTQ) control and prediction. The aim with RTQ is to actively manage product quality *a priori* during processing without the need to rely on post-manufacture quality testing (Hunter et al., 2012). Process Analytical Technology (PAT) is a widely used term that has been superseded by RTQ with additional focus on feedback control and active process improvement (Zhang et al., 2012). Munir et al. (2015) reviewed the current status of PAT in the dairy industry and argued that a more holistic PAT approach is necessary to get the full benefits of PAT. This conclusion is consistent with the aim of real-time product quality determination.

Quality in real time requires three key elements: process analysers with on-line mathematical tools that enable predictions; critical real-time 'actionable' information across the production line; and the subsequent timely plant feedback control. The way that these three elements work together is as follows: Multivariate information is collected through on-line or in-line process

* Corresponding author.
E-mail address: tajammal.munir@auckland.ac.nz (M.T. Munir).

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analysers and fed to on-line mathematical tools for real-time process monitoring that is then used to control the process and achieve in-specification product in real-time (Hunter et al., 2012).

A wide range of optical sensing techniques are emerging as potential new process analysers for the RTQ of milk powder such as spectroscopy and imaging. Various spectroscopic methods have been used in the milk powder industry mainly for compositional control, to standardise the fat, protein and moisture content of the powder (Cama-Moncunill et al., 2016; Holroyd et al., 2013; Schamberger and Labuza, 2006). While imaging systems have also been used in grading and quality control operations, according to Gowen et al. (2007), they tend to be inadequate identifiers of quality, and are not particularly efficient.

Hyperspectral imaging (HSI) is a well-established technique that is potentially suitable for this type of operation because it combines advantages of imaging and spectroscopy technologies while minimising their limitations. For example, spectroscopy does not include spatial information but spatial information is necessary for most food quality tests (García-Cañas et al., 2012; Gowen et al., 2007). However, both spatial and spectral information are obtained from a sample using HSI. Other advantages of HSI are that it is non-invasive, requires small samples and generates a large amount of information-rich data, which should provide additional information about milk-powder appearance. However relatively longer run-times are required for acquiring images, substantial computing power is needed to store and process 3D data, and such equipment is costly (Gowen et al., 2007; Kandpal et al., 2016).

Hyperspectral imaging technology generates a spatial map of spectral profiles. It collects a series of two-dimensional (x, y) images as a function of wavelength (λ), where each image plane maps the intensity of reflected light (absorbance) from the sample at a single wavelength, λ_i. This spatial map of spectral variations forms a three-dimensional 'hypercube' of image data (x, y, λ), through the superimposition of the 2D spatial images, as shown in Fig. 1 (a). Each spatial image of the hypercube is composed of pixels representing the reflection of a single wavelength. The full spectral response at each pixel position can also be shown across the layers as in the highlighted dark red squares in Fig. 1 (a). Consequently, the hyperspectral image can be viewed as a collection of spectra, $I(\lambda)$ at each pixel position (x, y). In total, this forms the 3D 'hypercube' $I(x, y, \lambda)$, as shown in Fig. 1 (b).

An HSI instrument generally acquires a rectangular image, so cropping may be needed to ensure only the actual sample is analysed. There are various techniques for background removal or region of interest (ROI) selection, including manual selection, or use of image histograms where sharp changes can differentiate sample bounds (Vidal and Amigo, 2012). In this study, the ROI was simply manually selected. The ROI can further be sub-sampled if required using (x, y) position information.

Hyperspectral imaging normally generates a large volume of data. In this study, a typical image was around 150 by 200 pixels giving ~30,000 pixels or observations measured at 933 equally spaced wavelengths from 400 to 1000 nm. The resultant data structure is a data cube with corresponding computer memory size requirement of around 100–250 Mb.

Outside the dairy industry, HSI has been used in a wide array of applications such as remote sensing (Goetz, 2009), airborne hyperspectral surveys (Giardino et al., 2015), astronomy (Hege et al., 2004), agriculture (Lelong et al., 1998), biomedicine (Fabricius and Pust, 2014), and mineralogy (Kruse, 2012), as well as non-dairy foods (Gowen et al., 2007). Hyperspectral imaging has a range of applications in the food industry. These range from the detection of foreign objects, product composition control and surface-quality monitoring. For example, Feng and Sun (2012) applied HSI for food safety inspection and control, Mehl et al. (2004) employed HSI for the detection of apple surface defects

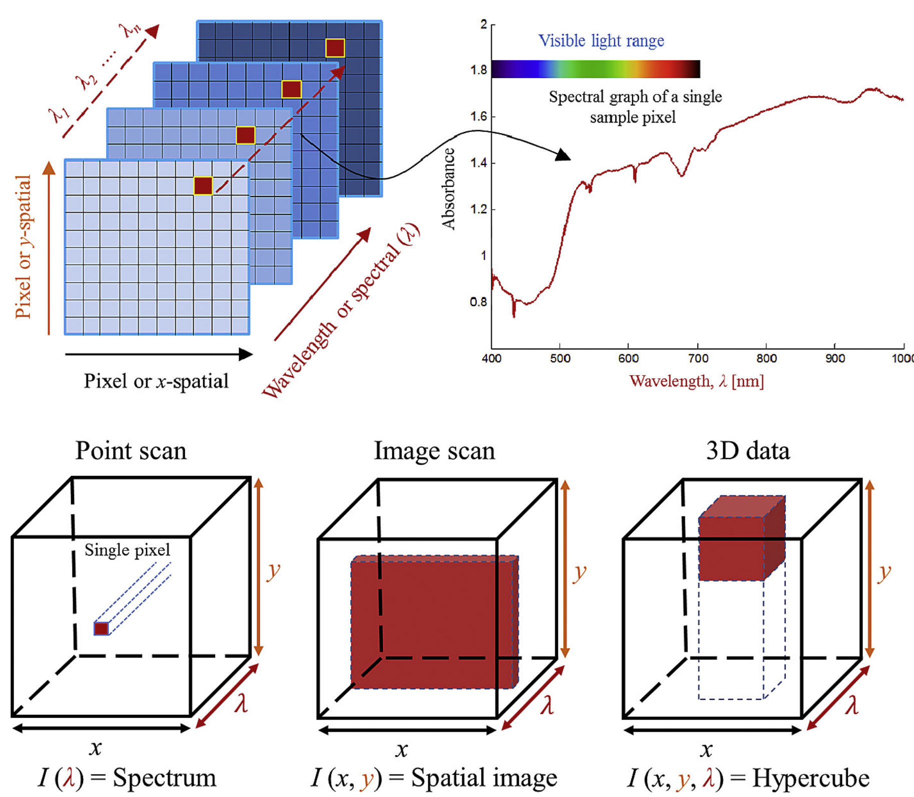

Fig. 1. Hyperspectral imaging (a) HSI images as a function of wavelength, and (b) HSI images data structure.

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