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Simple, fast, and low-cost camera-based water content measurement with colorimetric fluorescent indicator

Seok-Jeong Song [a], Tae-Il Kim [b], Youngmi Kim [b], Hyoungsik Nam [a,*]

[a] *Department of Information Display, Kyung Hee University, Seoul 02447, Republic of Korea*
[b] *Department of Chemistry, Kyung Hee University, Seoul 02447, Republic of Korea*

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ABSTRACT

Recently, a simple, sensitive, and low-cost fluorescent indicator has been proposed to determine water contents in organic solvents, drugs, and foodstuffs. The change of water content leads to the change of the indicator's fluorescence color under the ultra-violet (UV) light. Whereas the water content values could be estimated from the spectrum obtained by a bulky and expensive spectrometer in the previous research, this paper demonstrates a simple and low-cost camera-based water content measurement scheme with the same fluorescent water indicator. Water content is calculated over the range of 0–30% by quadratic polynomial regression models with color information extracted from the captured images of samples. Especially, several color spaces such as *RGB*, *xyY*, $L^*a^*b^*$, $u'v'$, *HSV*, and YC_BC_R have been investigated to establish the optimal color information features over both linear and nonlinear *RGB* data given by a camera before and after gamma correction. In the end, a 2nd order polynomial regression model along with *HSV* in a linear domain achieves the minimum mean square error of 1.06% for a 3-fold cross validation method. Additionally, the resultant water content estimation model is implemented and evaluated in an off-the-shelf Android-based smartphone.

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1. Introduction

Water can significantly affect some features of products akin to their physical characteristics, microbiological stability, and shelf life [1]. Even very small amount of water in the jet fuel causes a critical problem of forming ice crystals or orifices in the fuel system of an aircraft [2]. Regarding foodstuffs, measuring water content is one of the most frequent and important works. Therefore, accurate and fast water content estimation is highly demanded in many fields [3].

Some methods have existed to determine water content including drying oven method, chemical titration method, the iodine/pyridine method (Karl-Fischer method), and distillation method (Dean–Stark method) [4–7]. However, they have required specialized equipment, relatively lengthy assays, or long analysis time. Lately, a simple fluorometric method based on sensitive reaction-based sensing material has been proposed to indicate water content rapidly and easily by different visible emission colors [8]. Water content in the test sample changes the fluorescence intensities under the ultra-violet (UV) irradiation. Consequently, the proposed fluorescent indicator can simply present the amount of water with different colors from red to green. However, in order to measure water content in numeric values, a bulky and expensive spectrometer is unavoidable along with additional post processing.

This paper proposes a new camera-based water content measurement scheme with the previous colorimetric and fluorescent indicator. Instead of any heavy instruments that can measure the intensities over wavelengths, the proposed scheme takes a picture of the fluorescent indicator and converts the extracted color information into the water content value at the unit of%. In the end, this simple processing structure allows an off-the-shelf smartphone to measure water content easily and conveniently.

2. Color information extraction of camera-based water content measurement

The proposed scheme is put into action as depicted in Fig. 1. The indicator generates the fluorescence color corresponding to water content under the 365 nm UV irradiation. After the image of the fluorescent indicator sample is captured by a camera, the color information is extracted. Then, water content is measured through the regression model with given color information.

The proposed camera-based measurement is conducted by using a simple, rapid, and sensitive reaction-based colorimetric

* Corresponding author.
E-mail address: hyoungsiknam@khu.ac.kr (H. Nam).

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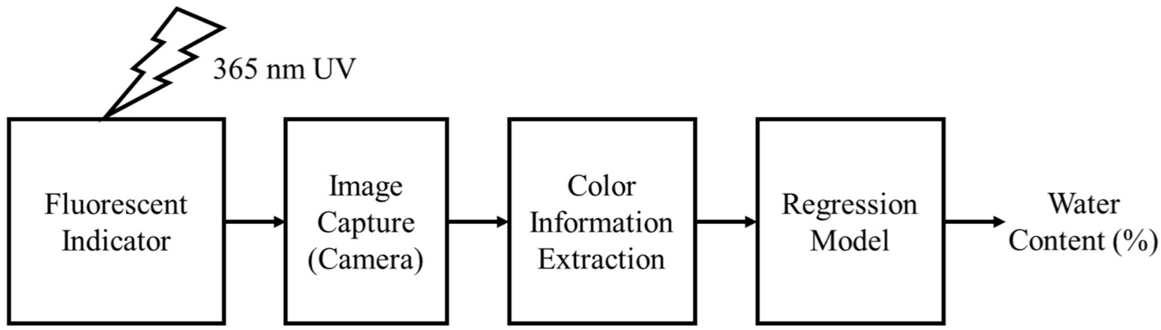

Fig. 1. Overall procedure of proposed camera-based water content measurement.

and fluorescent indicator for organic solvents, drugs, and foodstuffs [8]. After the indicator is put into solutions like tetrahydrofuran (THF) containing water, the fluorescent light is generated by exposing to the UV light. The amount of water in the solution results in the spectral change of the resultant light.

As water content in the solution increases, the intensity of green emission at 526 nm increases and the intensity of red emission at 618 nm decreases as shown in Fig. 2(a). Thus, the emission colors of indicators under an UV lamp change from red to green depending on water content in the solution as shown in the Fig. 2(b) where the whole 18 samples collected as 3 groups of 6 samples are given concerning water content from 0% to 30%. To expand the amount of the data for training and evaluating regression algorithms, 10 pixel points per one sample are extracted at the area around the center point. To alleviate the dependency between training and evaluating data, the 3-fold cross validation method is conducted [9]. That is, when 3 groups of samples are assigned with A, B, and C, the 1st run uses A and B for training and C for evaluating. The 2nd run utilizes B and C for training and A for evaluating and then the 3rd run makes use of C and A for training and B for evaluating. The final performance is evaluated with results of all 3 runs. Average $R^*G^*B^*$ values of three groups are shown in Table 1.

In order to realize the proposed water content measurement scheme, the optimal color information should be determined by weighing options of possible candidates that can be extracted through various color spaces [10–12]. Six color spaces of xyY, $u'v'$, $L^*a^*b^*$, HSV, YC_BC_R, and RGB are taken into consideration and their resultant color information values are calculated from RGB data provided by the smartphone. RGB data are obtained by converting an 8-bit *YUV420sp* format of a camera with (1) [13].

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.37075 \\ 1 & -0.33763 & -0.698001 \\ 1 & 1.732446 & 0 \end{bmatrix} \begin{bmatrix} Y \\ U-128 \\ V-128 \end{bmatrix} \tag{1}$$

By and large, the output RGB image of the camera is initially given after the process of nonlinear gamma-correction to address the perception of human beings. However, it is not certain that the perception is linked to the water content measurement. Thus, two versions of RGB data before and after gamma-correction are

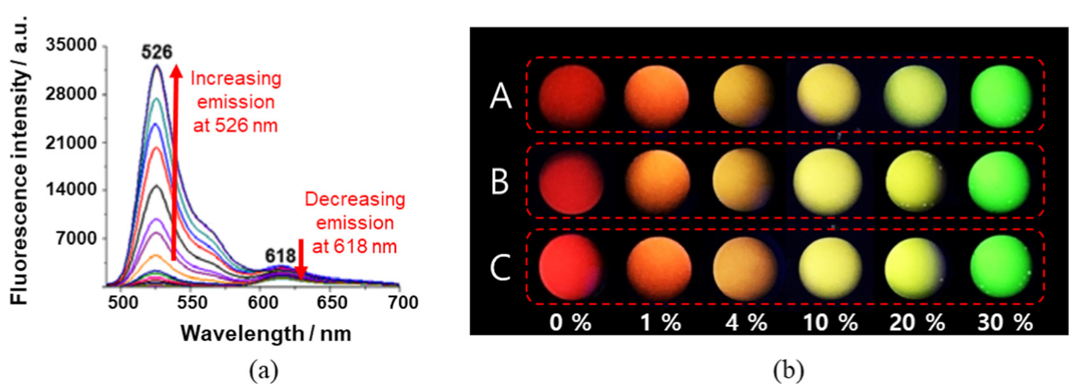

Fig. 2. Colorimetric and fluorescent water content indicator [8] (a) spectral changes over water content (b) photos of water content indicators for THF containing different amounts of water under 365 nm UV irradiation.

Table 1
Average $R^*G^*B^*$ values of three groups in Fig. 2(b).

Water content (%)	Group A			Group B			Group C		
	R^*	G^*	B^*	R^*	G^*	B^*	R^*	G^*	B^*
0	195	18	9	203	19	20	253	45	39
1	236	79	24	222	92	24	240	81	26
4	227	191	62	231	161	63	234	182	60
10	233	215	85	246	243	111	245	242	112
20	227	242	74	226	234	64	209	228	90
30	104	253	69	108	254	69	103	254	65

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