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Article

Optical Sensing Approach to Recognition of Different Types of Particulate Matters for Sustainable Indoor Environment Management

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Abstract: As climate changes, our daily life has been much influenced by abnormal meteorological phenomena such as heavy rainfall, heat wave, heavy snowfall, and fine dust. Atmospheric air quality is worsening day by day and indoor air quality is also affected by interconnected daily activities throughout the inside and outside of buildings and houses. Nowadays, pollutants from various sources are emitted, transformed by sunlight, vapor, and ozone and transported into the city from country to country. Due to these reasons, there have been high demands to monitor the transportation of particulate matters and improve air quality. Monitoring of pollutants and identification of type and its concentration enables us to track and control its generation and consequently find out the solution. However, monitoring of pollutants, especially, particulate matter generation and its transportation is still not fully operated in atmospheric air due to its open nature and meteorological factors. Even though indoor air is relatively easy to monitor and control than outdoor in the aspect of specific volume and contaminant source, but it still needs to consider the meteorological parameters because indoor air is not fully separated from the outdoor air flow and contaminants transportation. In this study, optical approach using spectral sensor was attempted to reveal the feasibility of wavelength and chromaticity values of reflected light from specific particles. From the analysis of reflected light of various particulate matters according to different liquid additives, parameter studies were performed to investigate which experimental conditions can contribute to the enhanced selective sensing of particulate matters. Five different particulate matters such as household dust, soil, talc powder, gypsum powder and yellow pine tree pollen were utilized and observed to elucidate the relationship between property of particulate matter and detected light spectrum. Applicable approaches to assist current particle matter sensors and improve the selective sensing were suggested.

Keywords: optical sensing; particulate matter; sustainable indoor environment; contaminant control

1. Introduction

There have been continuous necessities to control indoor air quality more precisely and in more detailed information. However, indoor air is quite different with atmospheric air in the aspect of air flow characteristics and type of contaminants [1]. Depending on the type of building and purpose of usage, contaminant type and its level varies due to the different human activity and emission source. For residential house, cooking is reported as a primary factor to emit gaseous pollutants such as formaldehyde, CO, and TVOC. Particulate pollutant $PM_{2.5}$ is also one of contaminants, highly detected in indoor air during the cooking [2]. Relatively large particulate matters such as soil dust, flower pollen and PM_{10} are well known to be transported into the indoor by air flow from the outside

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and their generation and behavior have been reported quite different [3]. Even though various technologies to detect both gaseous and particulate contaminants have been developed and widely applied to practical fields, any sensing data to inform us with both contaminant source and its concentration simultaneously does not exist and even its accuracy is still low [4]. Most commercial sensors to detect particulate matters are generally called to the dust sensor and are mostly based on the light scattering principle. As much of particles exist in a specific volume of sensor inside, more light is scattered and reflected to the detector and represented as of particle levels. For this reason, it is necessary to introduce sufficient air containing contaminants that can represent statistically mean concentration per volume into the sensor inside by fan or air compressor for reliable accuracy. The other factor to govern the dust level is the interaction between light source and particulate matters. Previous researches have been reported that light sources such as laser diode, infrared, and LED photodiode were examined how light source can influence the sensing of particulate matters [5,6,7]. Depending on the light source, single point detection, uniformity issue, and brightness difference were reported to limit the sensitivity of dust sensors [8]. For more accurate concentration, particle counters utilizing Beta ray absorption method were tested and authorized to report daily data of particulate matters those have aerodynamic diameter less than 10 and 2.5 μm in Korea [9]. According to the purpose of measurement, both optical sensing and beta attenuation monitoring (BAM) were adopted to research area or air pollution forecast, but simple light scattering based sensors were mostly utilized in daily life measurement for a single household air quality monitoring including dust sensor, air conditioner and air purifier. As recognized in the above explanations, the concentration of particulate matter is primary information for sensors in monitoring particulate matter contaminants and is provided relatively quite enough with various methods. However, other information such as type of particles, chemical composition to inform us with the origin where it is generated and transported from is still under laboratory level observation [10]. Nowadays, characterization to find out the origin of contaminants, especially in particulate matters, are one of major concerns in Korea because daily concentration of fine dust so called, $PM_{2.5}$ and PM_{10}, is so influential that number of patients with the respiratory disease is reported to be noticeably increased and personal protective equipment (PPE) including air pollution mask, filter and air purifier are sold significantly above the production amount. In several reports, particulate matters are characterized and chemical compositions are reported that PM_{10} and $PM_{2.5}$ contain organic compound (OC) and heavy metal ions, which may induce health issues [11]. So, there is at least demand to identify the type of contaminants by simple dust sensor at economic cost as a prescreening level test. In this study, two approaches were tested. Small scale spectral sensor was utilized to find the feasibility of light wavelength in terms of position and intensity to discriminate the type of particulate matters. The other approach was to use chromameter to reveal the color data of particulate matters in chromaticity diagram. Five different particles, soil, household dust, Korea pine tree pollen, talc powder, and gypsum powder were chosen and tested by analyzing the light spectrum and color data of reflected light under experimental conditions to change optical parameters. It is our expectation that combined data of reflected light spectrum and color can assist current light scattering based sensors to identify the type of particulate matter contaminants and concentration with higher accuracy.

2. Materials and Methods

Five different particulate matters were collected in Korea and prepared for the characterization as it is. Household dust was collected by regular vacuum cleaner. Korean pine tree pollen was collected during spring season in Korea by washing the glass plate located under the pine tree bush for one day. Illite powder, one of commonly found yellow soil in Korea, was used for the representative soil sample and it was purchased from Yong Gung Illite® Inc. Average particle size was characterized to be less than 200 μm. Talc powder, raw material of widely used construction material and usually suspended in air during the construction process was purchased from chemical company to have chemical formula $Mg_3H_2(SiO_3)_4$; $H_2Mg_3O_{12}Si_4$. All five samples were ground and filtered with Whatman® qualitative paper filter having 20 μm particle retention by flushing with

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distilled water to exclude the size induced difference. After drying at room temperature, collected powders were used for experiment.

Spectral sensor, Apollo™, developed by NanoLambda in Korea, was used to differentiate reflected light into light spectrum in a small chamber and to examine the applicability to small scale sensor. Configuration of chamber and detailed experimental method was described in our previous study [12]. Chromameter CR-400 by Konica Minolta was used to acquire color data in terms of chromaticity values.

Filters and liquid additives to modulate reflected light of particle samples were tested. Cellophane filters were ranged from red, orange, yellow, green, blue, pink, and violet in visible light range. Three color filters, dark blue, green, and yellow were utilized that belongs to 400~450nm, 500~550nm, and 550~600nm in wavelength, respectively. Two liquid additives, refractive index liquid (n=1.550, Cargille Inc.,) and distilled water were tested.

Reflected light was observed in the same 10cm distance from the sample surface to the detectors; spectral sensor and chromameter. 80W-6500K white LED light bulb was used for light source to provide sufficient light in visible light range and avoid light color effect. In addition to that, UV light with 365nm in wavelength.

3. Results

As described in introduction chapter, main purpose of this study was to find the feasibility of optical approaches in identifying the specific type of particulate matters among whole particulate mixtures in air and the influence of other parameters; filters and liquid additives on the selectivity in terms of light intensity, wavelength and chromaticity value. Spectral sensor and chromameter are tested respectively under same conditions by liquid additives. Chromaticity values in chromaticity diagram are in figures from 2 to 5. Details of conditions and results are denoted in tables from 1 to 5.

Table 1. Chromaticity values of household dust and soil powder samples measured under cellophane filter conditions.

		Chromaticity Values						Chromaticity Values			
Sample		Cellophane	Y	x	y	Sample		Cellophane	Y	x	y
Household Dust	As prepared	-	13.40	0.3229	0.3244	Soil Powder	As prepared	-	13.40	0.3229	0.3244
		Red	4.87	0.4216	0.3307			Red	4.87	0.4216	0.3307
		Orange	8.01	0.4625	0.3576			Orange	8.01	0.4625	0.3576
		Yellow	13.47	0.4230	0.4305			Yellow	13.47	0.4230	0.4305
		Green	5.08	0.2923	0.3853			Green	5.08	0.2923	0.3853
		Blue	3.16	0.2516	0.2058			Blue	3.16	0.2516	0.2058
		Pink	9.91	0.4098	0.2624			Pink	9.91	0.4098	0.2624
		Violet	4.40	0.2970	0.2686			Violet	4.40	0.2970	0.2686
	Water Added	-	5.18	0.3190	0.3208		Water Added	-	5.18	0.3190	0.3208
		Red	4.43	0.3869	0.3357			Red	4.43	0.3869	0.3357
		Orange	6.16	0.4197	0.3508			Orange	6.16	0.4197	0.3508
		Yellow	9.02	0.3955	0.4066			Yellow	9.02	0.3955	0.4066
		Green	4.41	0.3025	0.3586			Green	4.41	0.3025	0.3586
		Blue	3.11	0.2692	0.2320			Blue	3.11	0.2692	0.2320
		Pink	8.52	0.4081	0.2856			Pink	8.52	0.4081	0.2856
		Violet	4.35	0.3008	0.2851			Violet	4.35	0.3008	0.2851
	Refractive Index Liquid Added	-	3.48	0.3163	0.3177		Refractive Index Liquid Added	-	3.48	0.3163	0.3177
		Red	4.37	0.3768	0.3369			Red	4.37	0.3768	0.3369
		Orange	5.87	0.3859	0.3305			Orange	5.87	0.3859	0.3305
		Yellow	8.17	0.3756	0.3864			Yellow	8.17	0.3756	0.3864
		Green	3.92	0.3021	0.3635			Green	3.92	0.3021	0.3635
		Blue	4.29	0.2800	0.2699			Blue	4.29	0.2800	0.2699
		Pink	7.38	0.4170	0.2834			Pink	7.38	0.4170	0.2834
		Violet	3.39	0.3080	0.2797			Violet	3.39	0.3080	0.2797

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Table 2. Chromaticity values of talc powder and gypsum powder samples measured under cellophane filter conditions.

Sample		Cellophane	Chromaticity Values Y	x	y	Sample		Cellophane	Chromaticity Values Y	x	y
Talc Powder	As prepared	-	74.79	0.3127	0.3191	Gypsum Powder	As prepared	-	79.97	0.3157	0.3213
		Red	7.53	0.4932	0.3040			**Red**	8.52	0.5498	0.3143
		Orange	22.17	0.5568	0.3732			**Orange**	24.57	0.5630	0.3738
		Yellow	50.31	0.4682	0.4770			**Yellow**	53.23	0.4719	0.4763
		Green	12.40	0.2337	0.5337			**Green**	12.90	0.2382	0.5213
		Blue	3.84	0.1888	0.1134			**Blue**	3.99	0.1816	0.1021
		Pink	20.73	0.4025	0.2020			**Pink**	20.89	0.4078	0.1989
		Violet	4.57	0.2687	0.1634			**Violet**	3.74	0.2681	0.1400
	Water Added	-	47.39	0.3136	0.3205		Water Added	-	19.09	0.3065	0.3134
		Red	6.69	0.4999	0.3211			**Red**	5.07	0.4332	0.3300
		Orange	15.50	0.5189	0.3610			**Orange**	9.48	0.4626	0.3495
		Yellow	32.18	0.4565	0.4669			**Yellow**	16.81	0.4224	0.4363
		Green	8.73	0.2529	0.4859			**Green**	6.00	0.2818	0.4111
		Blue	3.61	0.2012	0.1323			**Blue**	4.44	0.2431	0.2094
		Pink	14.18	0.4069	0.2127			**Pink**	10.71	0.4011	0.2453
		Violet	3.57	0.2783	0.1835			**Violet**	4.35	0.2906	0.2543
	Refractive Index Liquid Added	-	15.30	0.3225	0.3297		Refractive Index Liquid Added	-	56.70	0.3159	0.3217
		Red	4.91	0.4221	0.3310			**Red**	7.34	0.5239	0.3181
		Orange	8.70	0.4525	0.3457			**Orange**	18.51	0.5450	0.3724
		Yellow	14.58	0.4276	0.4370			**Yellow**	37.61	0.4629	0.4703
		Green	5.23	0.2828	0.4115			**Green**	9.90	0.2457	0.5043
		Blue	3.21	0.2443	0.1962			**Blue**	4.91	0.2043	0.1460
		Pink	7.38	0.4170	0.2834			**Pink**	17.27	0.4064	0.2135
		Violet	3.39	0.3080	0.2797			**Violet**	3.54	0.2757	0.1664

Table 3. Chromaticity values of pine tree pollen measured samples under cellophane filter conditions.

Sample		Cellophane	Chromaticity Values Y	x	y	Sample		Cellophane	Chromaticity Values Y	x	y
Pine tree Pollen	As prepared	-	32.77	0.3938	0.3796	Pine tree Pollen	Water Added	-	28.76	0.3926	0.3846
		Red	6.79	0.4714	0.3017			**Red**	6.28	0.4887	0.3205
		Orange	14.02	0.5200	0.3524			**Orange**	12.88	0.5247	0.3614
		Yellow	24.74	0.4745	0.4402			**Yellow**	23.08	0.4626	0.4336
		Green	6.84	0.2764	0.4338			**Green**	6.30	0.2746	0.4422
		Blue	4.52	0.2479	0.2204			**Blue**	3.25	0.2432	0.1983
		Pink	13.51	0.4823	0.2669			**Pink**	13.54	0.4722	0.2769
		Violet	3.40	0.3286	0.2329			**Violet**	4.42	0.3174	0.2579
	Refractive Index Liquid Added	-	22.62	0.3892	0.3804		Refractive Index Liquid Added	**Green**	5.88	0.2844	0.4117
		Red	6.06	0.4374	0.3039			**Blue**	4.39	0.2589	0.2374
		Orange	11.17	0.5106	0.3595			**Pink**	11.28	0.4708	0.2735
		Yellow	19.14	0.4601	0.4351			**Violet**	3.35	0.3240	0.2506

3.1. Color Detection

Chromaticity diagrams of five samples were shown in figures from 2 to 5. As denoted in figures, all samples were prepared as dried, water added, and refractive index liquid added. Water and refractive index liquid were utilized to investigate the additional effect of additives on the reflected light by expecting the changes on refractive indices and associated colors as well. As explained in materials part, cellophane filter which can block specific range of wavelength depending on its color. Details of wavelength and color of each cellophane filter were drawn in consecutive color bars as

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shown in figure 1. For as-prepared samples, denoted to circle in diagram, were located with the coordinates x, y, Y in a diagram as of matching color circles according to the color of cellophane filter.

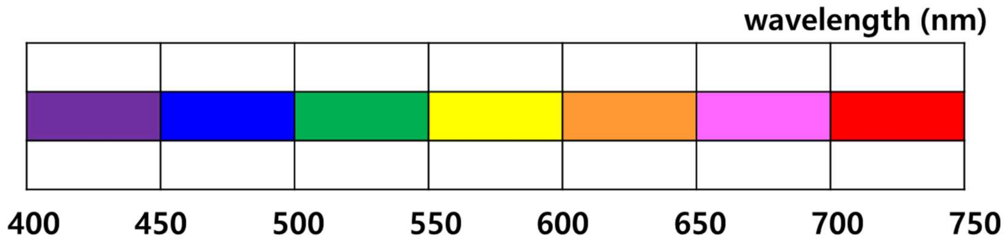

Figure 1. Color chart of seven cellophane filters in wavelength ranging in visible light from 400 nm to 750 nm. All colors represent the prepared colors of cellophane filters in specific wavelength range.

Here, coordinates; x, y, and Y represent color space and luminance value of reflected light, respectively [13]. Details of chromaticity values for household dust, soil powder and pine pollen are summarized in Table 1 and corresponds to chromaticity diagram in figure 2. For water added samples and refractive index liquid added samples were depicted as square and filled triangle, respectively as the above same manner. Prior to the detailed explanation, five samples can be simply divided into two groups, white-grey and yellowish groups after the bare-eye observation. Talc and gypsum powders belong to white group and other household dust, soil and pine tree pollen are regarded to non-white group.

Noticeable difference was measured for white color powders such as talc and gypsum samples. For white color powders, more distinct shifts to each color regions were measured rather than yellowish pollen, soil and grey household dust. It may be attributed to the intrinsic color of powder is close to white, more light reflected to the detector and induced to increased intensity to the spectral sensor. Meanwhile, other non-white; yellowish and grey powders were detected at lower intensity.

In addition, overall chromaticity values for yellowish powders were observed to shift into yellow region in diagram, upper left direction from central white region. Similar experiments were studied by Dang et. al. In their report, chromaticity value of five different color od inorganic pigments of drawing point revealed corresponding measured chromaticity value according to its color [14]. For water and refractive index liquid added cases, obvious differences in chromaticity values were observed. In figure 2-a) and 2-b), household dust revealed to shift more in yellow and red region, which correspond to long wavelength range in light spectrum. However, soil samples as shown in figure 2-c) and 2-d) were detected to have more movement in red and green region. In case of pollen sample, no significant change in chromaticity values were observed under additives conditions. For talc and gypsum powders, obvious shift for talc was observed only for refractive index liquid case and chromaticity values are centered in white region than any other samples. It is well described in previous study and are in accordance with results. This means that more white light is reflected to the chromameter detector [15]. For the comparison with talc, same experiments were executed for gypsum powder as shown in figure 3-c) and 3-d). Under chromameter measurement, no noticeable difference was observed. It means that similar color and particle shape does not differentiate the type of particle.

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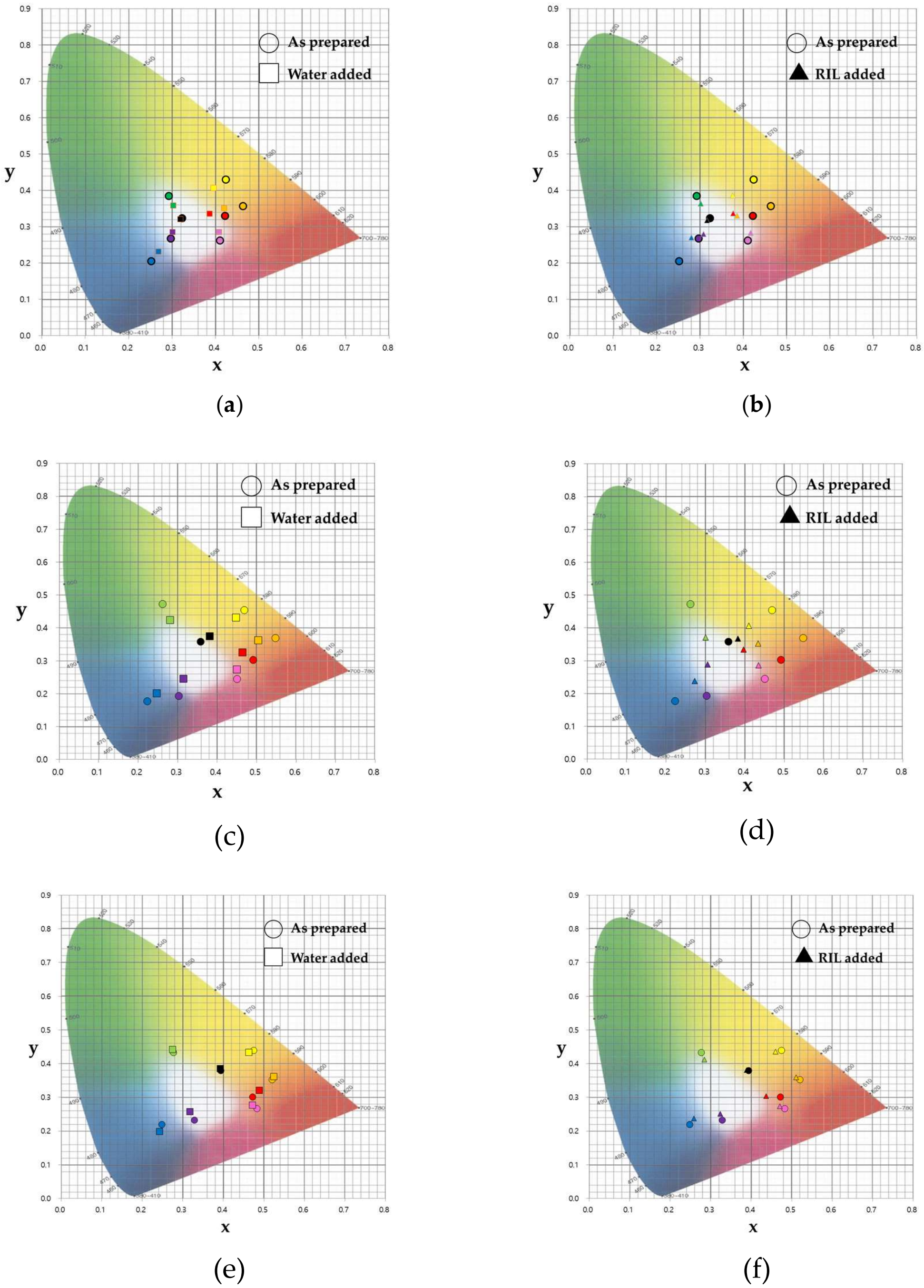

Figure 2. Chromaticity diagram of three different samples, household dust, soil dust, and pine tree pollen. All dots are chromaticity values (Y, x, y) and only x, y coordinates are denoted. Each figure is listed as: **(a)** as prepared (○) and water added (□) household dust; (**b**) as prepared (○) and Refractive Index Liquid (RIL) added (▲) **household dust**; (**c**) as prepared (○) and water added (□) soil dust; (**d**) as prepared (○) and RIL added (▲) **soil dust**; (**e**) as prepared (○) and water added (□) pine tree pollen; (f) as prepared (○) and RIL added (▲) **pine tree pollen**.

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3.2. Light Spectrum Detection

Spectral sensor was used to characterize the light spectrum of samples under experimental conditions. Figure 3-e) and 3-f) shows the spectrum of reflected light for household dust and talc powder as a function of wavelength. Same measurement was performed under different conditions. Details of measurements were summarized in table 4 and 5 according to peak position and peak intensity ratio. As shown in table 4 and 5, five samples revealed obvious difference in terms of peak position and peak intensity after additive treatment and cellophane filter usage.

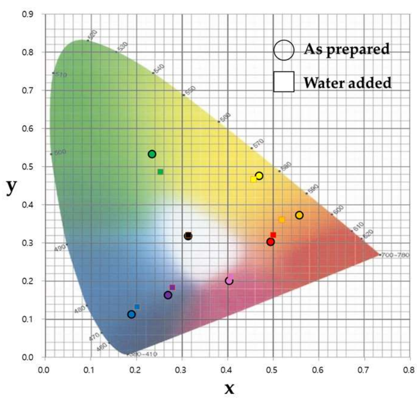
Table 4. Peak positions of detected reflected light of samples as a function of wavelength by spectral sensor under experimental conditions.

Sample conditions			As prepared			Water			Refractive Index Liquid		
Filter	Measurement	Materials									
No filter	Peak intensity		Low	High	Other	Low	High	Other	Low	High	Other
	Peak Positions (nm)	Pine tree pollen	421	681	601	421	681	591	421	676	721
		Soil	421	681	597	421	677	721	421	681	-
		Household Dust	420	678	-	420	677	720	420	677	-
		Talc	420	677	720	420	680	720	420	677	720
		Gypsum	420	679	-	433	691	-	433	690	-
Pink filter	Peak intensity		Low	High	Other	Low	High	Other	Low	High	Other
	Peak Positions (nm)	Household Dust	440	-	-	440	-	-	440	-	-
		Talc	430	-	-	430	490	-	430	-	-
		Gypsum	439	820	-	453	-	-	453	-	-

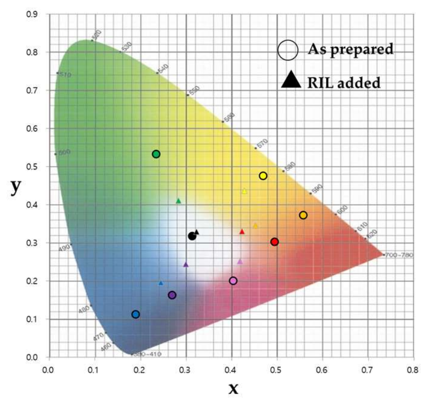
Table 5. Peak intensity ratio of detected reflected light of samples as a function of wavelength by spectral sensor under experimental conditions.

Sample conditions			As prepared			Water			Refractive Index Liquid		
Filter	Measurement	Materials									
No filter	Peak intensity		Low	High	Other	Low	High	Other	Low	High	Other
	Peak Intensity Ratio	Pine tree pollen	1	10.46	0.98	1	8.75	0.14	1	5.86	0.81
		Soil	1	8.51	0.14	1	4.61	0.41	1	8.12	-
		Household Dust	1	9.31	-	1	6.31	0.44	1	9.56	-
		Talc	1	6.32	0.45	1	4.51	1.41	1	6.21	0.68
		Gypsum	1	9.63	-	1	9.65	-	1	9.71	-
Pink filter	Peak intensity		Low	High	Other	Low	High	Other	Low	High	Other
	Peak Intensity Ratio	Household Dust	0.48	-	-	0.30	-	-	0.39	-	-
		Talc	0.21	-	-	0.08	0.06	-	0.21	-	-
		Gypsum	0.36	0.13	-	0.40	-	-	0.44	-	-

In table 5, peak intensity at each wavelength was calculated in a ratio. The peak intensity values at low wavelength for samples are regarded to "1" as a base then, peak intensities at other higher wavelengths were divided by base peak intensity. After pink filter usage, overall light intensity decreased and calculated with the same method for three household dust, talc and gypsum samples. Therefore, higher ratio value means relatively strong peak and vice versa. Two representative samples, household dust and talc powder were graphed to scrutinize the light spectrum changes by additives and filter and compared by peak position in wavelength and peak intensity as well. In case of household dust, two peaks at 420 and 678nm in wavelength were observed. Under pink filter, the peak at 678 nm was observed to be removed and peak shift from 420 to 440 nm was also observed. It is due to the light filtering at long wavelength range by pink cellophane. Even water and refractive index liquid are added, no significant shift was observed. These results correspond with the measured chromaticity values well under additives. Previously discussed chromaticity values in figure 2-a) and b), overall values are centered to the white region and relatively more shifts for blue, red, and yellow region were observed after refractive index liquid was added. Meanwhile, talc powder revealed slightly different results with that of household dust. Light spectrum for as prepared talc powder shows three peaks at 420, 677, and 720 nm, respectively. Two peaks at 420 and 677 nm showed relatively low ratio value as of 6.32, but no noticeable changes were observed for both additives to have ratio values as of 4.51 and 6.21 in table 5. Considering that combined condition of pink filter and water addition, peak shift from 420 to 430 nm and additional peak is observed at 490 nm. Other peaks at long wavelength range were filtered same as before. For the comparison, similar gypsum power was also characterized under pink filter and additives conditions. The peak at short wavelength region shifted from 420 to 453nm, but it was a big difference that additional peak observed for talc case at around 490nm was not detected. Instead of this, additional peak at around 820 nm was detected for water added gypsum sample. These results appear to be correlated with the absolute amount of shift in chromaticity values is larger for gypsum than that of talc powder.



(a)



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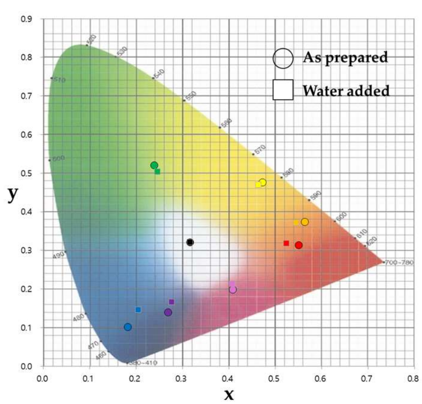
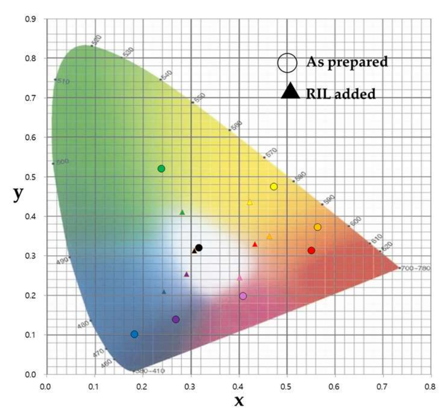


(c)



(d)

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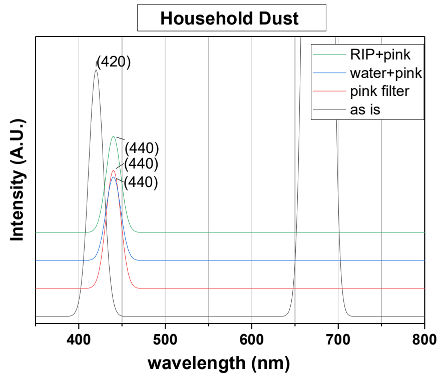
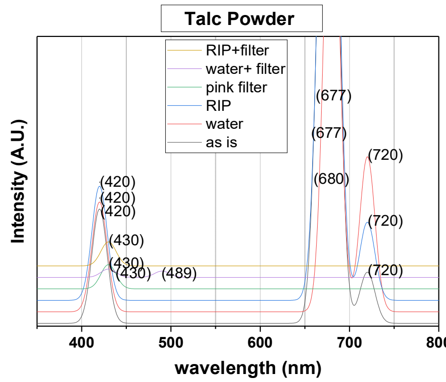


(e)



(f)

Figure 3. Chromaticity diagrams of samples under pink cellophane filter; (a) as prepared (○) and water added (□) talc powder; (b) as prepared (○) and RIL added (▲) talc powder; (c) as prepared (○) and water added (□) gypsum powder; (d) as prepared (○) and RIL added (▲) gypsum powder; (e) Spectrum of reflected light of household dust according to the sample as prepared(black), pink filter(red), water + pink filter (blue), and RIL + pink filter(green); (f) Spectrum of reflected light of talc powder according to sample status as: as prepared(black), water added(red), RIL added(blue), pink filter(green), water+pink filter(violet), and RIL+ pink filter(brown)

4. Discussion

Chromaticity diagrams were constructed and light spectrum graph was drawn according to different particulate matters under experimental conditions. Obvious change in chromaticity values were observed for water and refractive index liquid were added cases. Depending on the intrinsic color of samples, yellowish pollen and soil showed relatively shift to yellow region, and white powders such as talc and gypsum moved to white centered region after adding water or refractive index liquid. From the comparison with light spectrum. Noticeable relationship between shift in chromaticity values and position in wavelength according to the type of sample under filter and additives. More distinct dependency on filter color was observed for intrinsic white color powders such as talc and gypsum rather than household dust, pollen and soil. Peaks at 420nm appears to be the guideline peak to determine the influence of filter and additives depending on the type of sample. It was well agreed with method called "browning index" in other color and light characterization method by using spectrophotometer [16].

5. Conclusions

Color and light spectrum assisted optical sensing of particulate matters was operated in laboratory scale and controlled experimental conditions. From the chromaticity values and reflected light spectrum in terms of wavelength and intensity revealed the difference between samples according to color and water or refractive index liquid additives. Noticeable results can be summarized as below.

- Different types of particulate matters can be found in indoor environment by the transportation from outside atmosphere and two optical approaches observing color and reflected light were tested to find out the feasible parameters such as wavelength and chromaticity value or its combination
- Depending on the intrinsic color of as-prepared sample, some noticeable results were deduced.
- Liquid additives such as water and refractive index liquid could influence both color and light spectrum by shifting chromaticity value and wavelength.

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- Cellophane filter also could modulate optical measurement results by moving color region in chromaticity diagram and light spectrum along wavelength.
- By combining liquid additive and light filter, certain type of particulate matter was observed to have distinct chromaticity value and light spectrum.
- Specifically, household dust was found to locate at center region in chromaticity diagram with relatively higher portion and this tendency was enhanced under additives.
- Soil powder showed most obvious movement in chromaticity value under red and green cellophane filters and measured value in red region shifted more after water addition.
- Pine tree pollen have its derivative yellowish color and same results were observed by chromameter. Slight changes in experimental conditions were observed, but its tendency was relatively low
- Talc and gypsum powders have original white color as-prepared and revealed more dependence on refractive index liquid than other samples. However, under pink cellophane filter, talc and gypsum powder could be differentiated by water addition and additional peak observation at around 490 and 820 nm, respectively.

It was our observation that noticeable relationship between chromaticity values and light spectrum depending on the type of particulate matter. Appropriate combination of chromameter and spectral sensor can be an alternative approach to detect particulate matters with higher selectivity. In future studies, various colors of particulate matters are required to be characterized to find out the relationship intrinsic color of particles and optical identification. It is also our hope that fine particulate matters less than 10 and 2.5 μm in aerodynamic diameter should be separated to investigate the size dependence under the above approaches.

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