



## Research article

# A study of cyanobacterial bloom monitoring using unmanned aerial vehicles, spectral indices, and image processing techniques

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## ABSTRACT

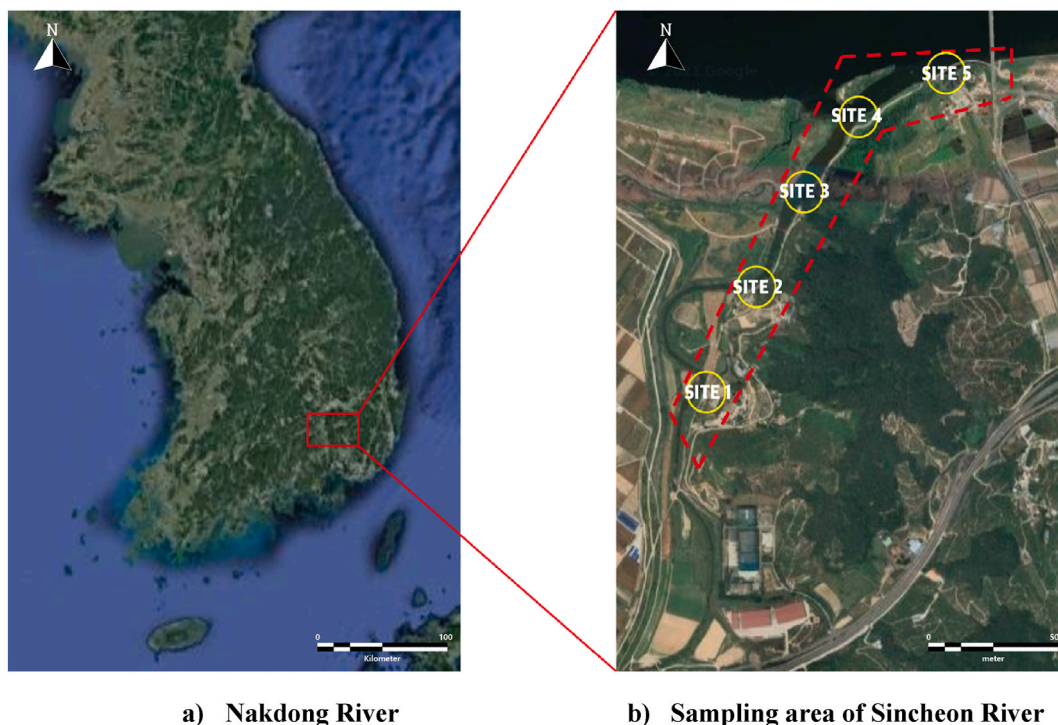
Last 5 years, the deterioration of water quality caused by algal bloom has emerged as a serious issue in Korea. The method of on-site water sampling to check algal bloom and cyanobacteria is problematic by only partially measuring the site and not fully representing the field, while at the same time, consuming a lot of time and manpower to complete it. In this study, the different spectral indices reflecting the spectral characteristics of photosynthetic pigments were compared. We monitored harmful algal bloom and cyanobacteria in Nakdong rivers with multispectral sensor images from unmanned aerial vehicles (UAVs). The multispectral sensor images were used to assess the applicability of estimating cyanobacteria concentration based on field sample data. Several wavelength analysis techniques were conducted in June, August, and September 2021, when algal bloom intensified, including the analysis of images from multispectral cameras using normalized difference vegetation index (NDVI), green normalized difference vegetation index (GNDVI), blue normalized difference vegetation index (BNDVI), and normalized difference red edge index (NDREI). Radiation correction was performed using the reflection panel to minimize interference that could distort the analysis results of the UAVs image. Regarding field application and correlation analysis, correlation value of NDREI was the highest at 0.7203 in June. And NDVI was the highest at 0.7607 and 0.7773 in August and September, respectively. Based on the results obtained from this study, it is found that it is possible to quickly measure and judge the distribution status of cyanobacteria. In addition, the multispectral sensor installed to the UAV can be considered as a basic technology for monitoring the underwater environment.

## 1. Introduction

In the past decades, climate change has been impacting the aquatic ecosystems of areas where reservoirs or barrages are built in rivers [1]. Among them, algal bloom caused by algae growth is a major problem in water quality [2]. Due to the mass proliferation of algae, rivers used as water sources are likely to deteriorate the function of water treatment filters and generate toxic substances due to cyanobacteria [3]. These cyanobacterial blooms can affect water quality by producing water soluble neurotoxic compound, which is potentially harmful to humans and animals including fish [4]. In Korea, the number of harmful cyanobacteria cells has been unified as an algal bloom warning indicator for systematic algal management since 2016. Therefore, there is a need for a monitoring method to minimize damage caused by cyanobacteria and to secure water source safety.

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**Fig. 1.** Location of the study area and sampling area a) Nakdong River b) Sampling area of Sincheon River.

Currently, the Ministry of Environment of Korea has designated 4 major rivers and the near areas as the algal bloom warning point and continuously monitors them (NIER, 2020). The Nakdong River is the second largest river in Korea and experiences severe algal blooms every year due to its high concentration of nutrients (T-N, T-P) (Bae and Seo, 2018). Algal blooms in Korea are known to occur mainly in small rivers and spread to rivers by slowing the flow rate and increasing the water residence time after the construction of the dam on the Geum river and Nakdong river in 2012 (Kim et al., 2021; Kim et al., 2021). However, Korea has a small number of observation areas, which makes it difficult to express adequately the site with data for each point within the continuous monitoring observation areas [5]. Also, in terms of water quality management, the method of sampling on-site water consumes a lot of manpower and time, so the number of observation points is limited [6]. Remote sensing techniques using satellite or aerial images supplement these limitations to observe large areas more quickly. Among them, drones and UAVs that are easy to access and can quickly observe large areas at once are used in various ways. Although the observation areas covered by UAVs are smaller than those of satellites, the UAVs have the advantage of high spatial resolution, ease of data acquisition, and atmospheric interference reduction to clouds and aerosols. UAVs are especially used for flood and lake monitoring [7], detection of water pollution [8], and chlorophyll-a concentration measurements [9].

Nowadays, there are many small rivers, reservoirs, and lakes in Korea, but measuring chlorophyll and phycocyanin concentrations through remote sensing techniques in such areas is limited because satellite images have problems evaluating small reservoirs, rivers, and lakes (10–30 m) due to their low spatial resolution [7]. The solution to this problem is to attach a multi-spectral sensor to UAVs. Multispectral sensors can be installed on UAVs to obtain high spatial resolution images of less than 0.15 m. The monitoring technology that can be mounted on UAVs makes more accurate measurements possible with the ability to build spatial information quickly and accurately [10]. For this reason, UAVs are more suitable for conducting image processing on rivers and streams.

Remote sensing studies of algal bloom using UAVs are expressed by indexing the characteristics of the active spectrum by photosynthetic pigments contained in algae, such as normalized difference vegetation index (NDVI), chlorophyll absorption ratio index (CARI), Three-Component Beamforming Explorer Method (3-BEM), etc. In addition, to date, most studies on algal bloom have analyzed substances by measuring the reflectance of chlorophyll-a using hyperspectral sensors attached to satellites or manned aircraft [11–15]. According to previous studies by this research team, algal blooms originate in small rivers and move to large rivers comprising small rivers, and then proliferate in large volumes and grow at high concentrations in large rivers. The rivers and lakes in Korea are rich in nutritional salts, and algal blooms begin in June when seasonal insolation is concentrated, and intensify from August to September. Also, algae grow until October when precipitation is low. Therefore, the primary purpose of the present study was to investigate the quantitative study of cyanobacterial bloom monitoring through the calibration of wavelength analysis technology of one image and field sample data taken using the spectral function of UAVs. To quickly monitor the status of cyanobacteria with the phycocyanin content of rivers using UAVs, the occurrence of algal blooms among several indices used for image analysis for detecting marine algae or observing vegetation on land were used. Comparison analysis was performed using four indices: NDVI, green normalized difference vegetation index (GNDVI), blue normalized difference vegetation index (BNDVI), and normalized difference red

**Table 1**  
Wavelength and bandwidth of UAVs multispectral camera.

Band name	Center wavelength (nm)	Bandwidth (nm)
Blue	475	20
Green	560	20
Red	668	10
Red Edge	717	10
Near IR (NIR)	840	40

**Table 2**  
Equations of the spectral index used in the study.

Name	Abbrev.	Type	Equation
Normalized difference vegetation index	NDVI	Red–NIR	$(R_n - R_r)/(R_n + R_r)$
Green normalized difference vegetation index	GNDVI	Green–NIR	$(R_n - R_g)/(R_n + R_g)$
Blue Normalized difference vegetation index	BNDVI	Blue–NIR	$(R_n - R_b)/(R_n + R_b)$
Normalized difference red edge index	NDREI	RE–NIR	$(R_g - R_r)/(R_g + R_r)$

edge index (NDREI). The comparative analysis of the multispectral sensor images was intended to evaluate the applicability and reliability of calculating the phycocyanin concentration estimation equation.

## 2. Material and methods

### 2.1. Field site and measurements

The research area is Sincheon River in the Nakdong River Basin located in Changwon-gun, Gyeongsangnam-do, Korea, shown in Fig. 1a and b. The Sincheon River is an area with many farmlands nearby. In addition, it is an area where algal bloom occurs often, and drinking water problems and odor disturbances come up every year. The red dotted line indicates the range of the area photographed by the UAVs, where the temperature, pH, dissolved oxygen (DO), electric conductivity (EC), and phycocyanin were measured directly. Temperature, pH, DO, and EC were measured using an EXO-YSI Sonde (EXO1 Multiparameter Sonde, YSI Inc., USA), and phycocyanin was measured after calibration using a phycocyanin standard solution in an Aquaflour fluorometer (Aquaflour handheld fluorometer, Turner designs, USA) before measurement [16]. The study period was June when algal bloom occurred, and August and September when algal blooms intensified. July was excluded from the study period because it was difficult to operate UAVs due to the rainy season.

### 2.2. UAVs and multispectral camera

The UAVs (FireFLY6, BirdsEyeView Aerobotics, USA) used in this study is a fixed-wing aircraft (vertical takeoff and landing). The specifications of the UAVs are: wing length 1523 mm, aircraft length 823 mm, aircraft weight 4.5 kg, loading capacity 0.7 kg, and cruising speed 15–18 m s<sup>-1</sup>. The UAVs consist of an expanded polyolefin (EPO) foam body covered with a carbon fiber frame and have rotating wings for landing. In addition, an automatic flight is possible and a global positioning system (GPS) and inertial measurement unit (IMU) are installed inside the aircraft so it can automatically fly on a designated route. The ground control system (GCS) was used to correct deviations. The observation altitude was 150 m and the ground sample distance (GSD) was 11.3 cm. In this study, the flight using the UAVs took 9 times. This is because, depending on the time the UAVs fly, the reflectance of sunlight, changes in wind speed direction change, and the correction value change.

The absorption wavelength for phycocyanin, a pigment containing cyanobacteria, is known to be measured using a reflectance ratio in the range of 615 nm–660 nm, so it is appropriate to use the multispectral camera in this study [17]. The multispectral camera (RedEdge, MicaSense, USA) used 1.22 megapixel (1280 × 960) sensors and collected reflectance information on the wavelength band's red, green, blue, near-infrared (NIR), and red edges. The calibration of the sensor was performed by entering the sensor sensitivity value of the sensor lens using the reflection panel. Table 1 shows the width of the wavelength captured by the multispectral camera. The Downwell light sensor (DLS) mounted on the aircraft's top provided proper lighting. A calibration reflectance panel (CRP) was used to determine the reflectance value which can calculate 0 to 1 as an exchangeable image file format (EXIF) value. DLS and CRP images were created and then corrected using Pix4Dmapper Pro software, and orthographic images used in the study were produced using Agisoft PhotoScan for georeferencing and stereotactic correction [18,19]. In addition, image processing by correcting CRP, DLS, EXIF, etc. using UAVs is one of the important tasks currently being studied (Kislik et al., 2018).

### 2.3. NDVI, GNDVI, BNDVI, and NDREI assessment

For all algae-related spectral indices, it is common to evaluate the NDVI, GNDVI, BNDVI, and NDREI indices (Duarte et al., 2018, Kislik et al., 2018). NDVI is an index that shows vegetation in the area by using data captured through remote exploration. NDVI

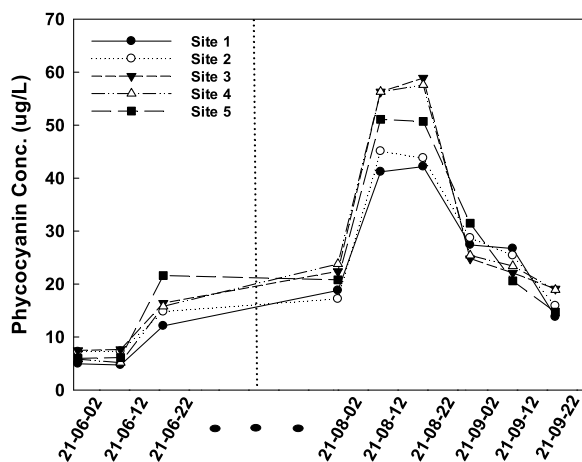


Fig. 2. Measured phycocyanin concentration at each site.

represents the vegetation distribution characteristics with a value between  $-1$  and  $+1$  [20].

In this study, NDVI evaluation was applied to the estimation of phycocyanin concentrations using red (668 nm) and near-infrared wavelengths. GNDVI was applied to the river to study by using green (560 nm) and near-infrared rays, BNDVI was blue (475 nm) and near-infrared rays, and NDREI was applied to the rivers using Red Edge (840 nm) and red. Table 2 summarizes the equations of each spectral index applied to the UAVs multispectral sensor image.

Where  $R_n$  is near infrared,  $R_r$  is red wavelength,  $R_g$  is green wavelength and  $R_b$  is blue wavelength. Each factor applies for calculating spectral index.

#### 2.4. Spectroscopic image data processing

Geometric correction of images taken by UAVs requires information recorded in the images, including georeferencing and GPS information (latitude, longitude, altitude, etc.). This information is stored in GPS sensors in the UAV and in each picture in the IMU. To improve the accuracy of geometry correction, 11 ground control points (GCPs) were set up. A reflectance panel was used to correct radiation because the reflection scattering value varies depending on the position of the photo in relation to the position of the sun. After the above process, individual images appear as one orthophotography.

To compare image data with actual data, *in-situ* measurements must be collected from the ground, as well as from the time the UAVs data is collected. To collect samples and data at approximately the same time during the acquisition of UAVs data, water quality data were measured in real-time by using EXO-YSI Sonde (EXO1 Multiparameter Sonde, USA).

By comparing and analyzing orthophotography and actual data, the phycocyanin concentration estimation value was calculated by the equation as the correlation between each spectral index and the phycocyanin test analysis value to calculate the determination coefficient ( $R^2$ ).

### 3. Results and discussion

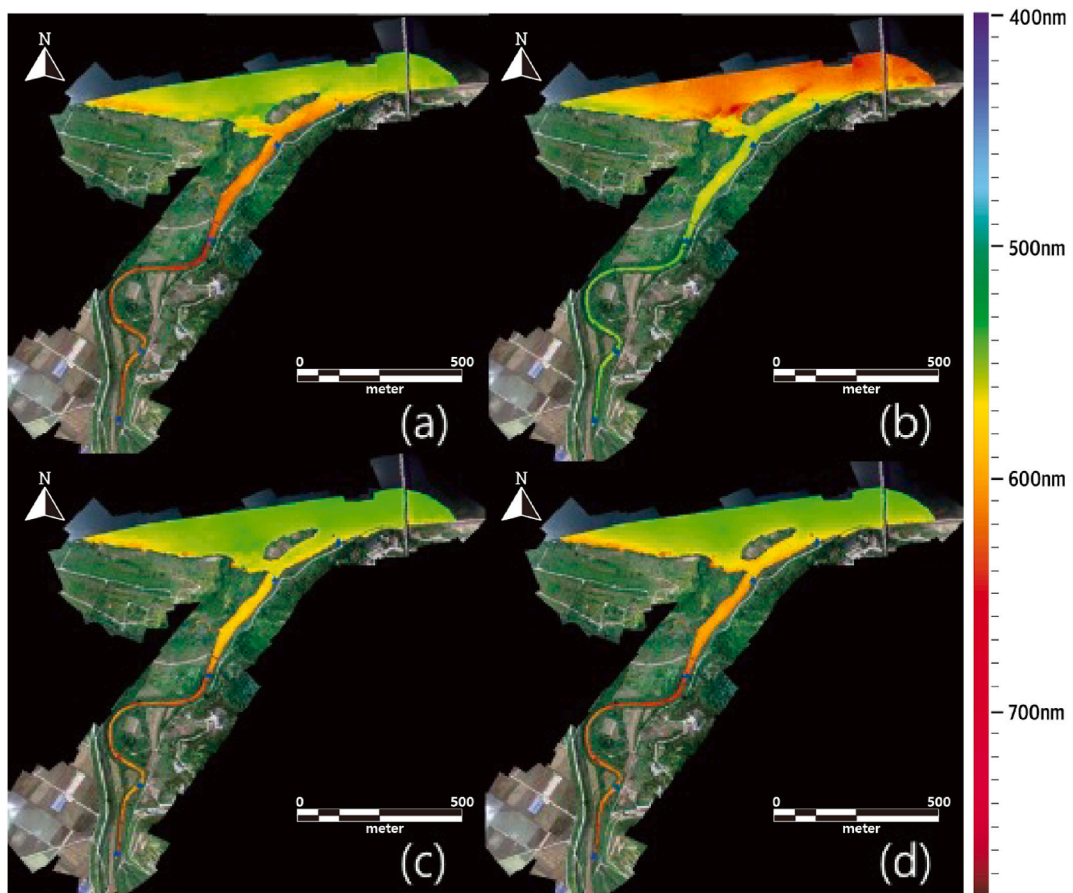
#### 3.1. Analysis of *in-situ* sample data

As a result of calibration by serial dilution of the phycocyanin standard solution in Aquaflo fluorometer (Aquaflo handheld fluorometer, Turner designs, USA), the  $R^2$  obtained was 0.993, which was reliable and suitable for measuring the concentration of cyanobacteria in the field. The change in the concentration of phycocyanin at five points in June, August, and September of the study area is shown in Fig. 2. Solar radiation and water temperature increase in June, and nutritional salts generated from fertilizers also flow into the aqueous system due to active agricultural activities in Korea. Therefore, it was confirmed that algae and cyanobacteria increased in June. Cyanobacteria contain microcystin, which is harmful to the human body, but research related to it is currently lacking, so the development of a monitoring method is important [21]. A study of the Nakdong River basin confirmed the distribution of harmful microcystin in cyanobacteria increased from 29.4% to 38.8% from June to August and decreased to 14.8% in September [22]. Therefore, the period from June to August, the peak of solar radiation and water temperature, reaches the high point of algal bloom, and as the environmental conditions required for green algae and cyanobacteria growth deteriorate in September, the rate of algae and cyanobacteria prosperity decreases [22]. The concentration of phycocyanin is known to be affected by various factors, including algae, water temperature, pH, and nutrient levels. (Bing et al., 2020).

Table 3 shows the maximum, minimum, and average values of temperature, pH, DO, EC, and phycocyanin concentrations for each site in June, August, and September. During this period, the pH range of sites 1–5 was 7.14–9.32, the DO range was 8.32–11.4 mg/L, the temperature was 24.2–33.3 °C, the electrical conductivity was 122–316  $\mu\text{S}/\text{cm}$ , and the range of phycocyanin was 4.74–58.9  $\mu\text{g}/\text{L}$ .

**Table 3**  
Minimum, maximum, and average values of temperature, pH, DO, EC, and phycocyanin of each site.

Sampling Point		Temp. (°C)	pH	DO (mg/L)	EC (uS/cm)	phycocyanin (ug/L)
Site 1	Min.	24.5	8.54	8.75	130	4.74
	Max.	31.8	8.76	11.40	272	42.21
	Avg.	27.6	8.63	10.15	198	21.3
Site 2	Min.	25.8	7.14	8.32	122	7.22
	Max.	31.2	8.72	11.38	286	45.1
	Avg.	27.8	7.92	9.40	194	22.8
Site 3	Min.	24.9	7.09	9.19	129	7.48
	Max.	32.5	9.17	10.7	316	58.9
	Avg.	27.6	8.23	10.13	207	26.13
Site 4	Min.	24.2	7.70	9.31	127	5.16
	Max.	33.3	9.32	11.1	301	57.6
	Avg.	27.5	8.46	10.14	205	25.80
Site 5	Min.	24.7	7.87	8.51	131	5.97
	Max.	31.0	8.38	9.90	292	51.1
	Avg.	27.3	8.18	9.32	202	24.79



**Fig. 3.** Image processing in June (a) NDREI, (b) NDVI, (c) GNDVI (d) BNDVI.

The concentration of phycocyanin was analyzed directly in the field to have a very close correlation between water temperature and electrical conductivity. Water temperature acts as a limiting factor in the growth of phytoplankton, and electrical conductivity indirectly indicates the presence of nitrogen and phosphorus, which are nutrient salts dissolved in the aqueous system [23,24]. Therefore, the  $R^2$  between phycocyanin and water temperature was obtained as 0.98 and 0.99 in the electrical chart, and the algae at the study site were evaluated to be dependent on environmental conditions without other growth inhibitors. However, measurement methods using UAVs can have negative effects depending on seasonal and environmental factors (rain, solar radiation, wind, etc.). Based on this study, it is considered that further research is needed.

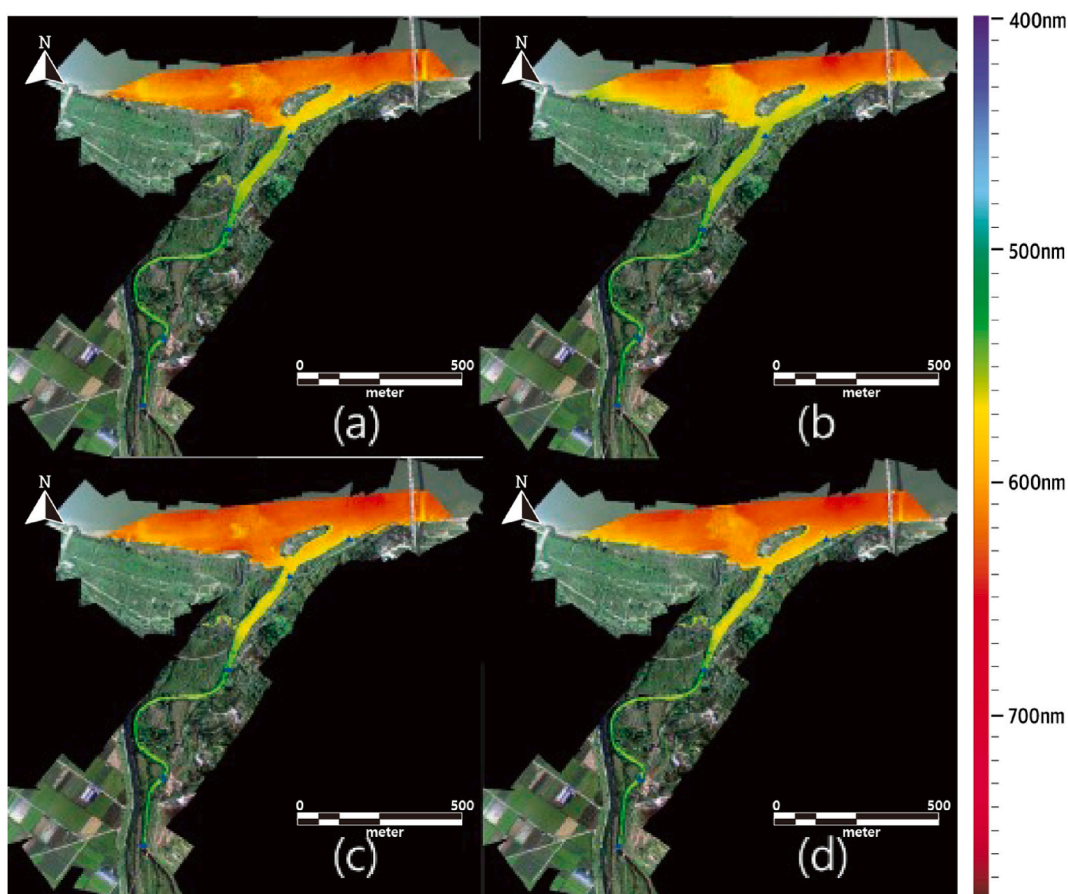


Fig. 4. Image processing in August (a) NDREI, (b) NDVI, (c) GNDVI (d) BNDVI.

### 3.2. NDVI, GNDVI, BNDVI, and NDREI assessment

Image processing with UAVs evaluate the concentration and distribution of phycocyanin for a wide range of confluence, including five points for in-situ water quality analysis. To evaluate the accuracy and reliability of the image processing task, correlation analysis was performed on the measured values of the image and in-situ sample analysis using each spectral index NDVI, GNDVI, BNDVI, and NDREI, and applicability was evaluated by comparing statistical significance to the experimental results. In all studies, Pix4Dmapper Pro software was used to remove distortion caused by shaking or tilting of the UAVs. Pix4Dmapper Pro is one of the most used software for image processing procedures in aerial photogrammetry [25]. Certain atmospheric factors can have a significant effect on the index values due to the high placement altitude (800,000–900,000 m). However, atmospheric disturbance of UAVs is minimized due to the low placement altitude (100–500 m) [26]. This is why the atmospheric disturbance was not corrected in the study.

As shown in Figs. 3a–d, 4a–d, and 5a–d, image analysis using NDVI, GNDVI, BNDVI, and NDREI was mainly conducted from June to September. The wavelength bands of the UAV spectroscopy applied to the spectral index (equation, calculation) were blue (475 nm), green (560 nm), red (668 nm), red-edge (717 nm), and near-infrared (840 nm). The calculation methods for each index are shown in Table 4.

In this study, the NDVI, one of the most widely used techniques in algae detection research using satellite image analysis, was evaluated first. NDVI is expressed as a value between  $-1$  and  $1$ . Vegetation areas are known to have close to zero values in clouds, artificial structures, rocks, etc. and water bodies such as rivers and ocean have negative values [27,28]. In this study, the correlation between NDVI and phycocyanin was  $0.7607$  and  $0.7773$  in August and September, respectively, when the algal bloom intensified. It showed a statistically significant level compared to other indices. In another study, as a result of image analysis using drones, NDVI was unable to perform reliable index evaluation due to the dominant spectral characteristics for light reflectance [29]. However, in this study, NDVI was evaluated by measuring the reflectance of the reflection panel and applying the correction value for light. Because the spectral characteristics of the cyanobacteria flowering region are similar to those of green plants, NDVI can be used as one of the effective indicators to extract cyanobacteria flowering information [30]. Ma et al. (2021) confirmed that harmful algae growth data could be extracted with an accuracy of  $96.1\%$  using the NDVI method.

The correlation between GNDVI and phycocyanin, which are representable for the green wavelength band, was derived from the

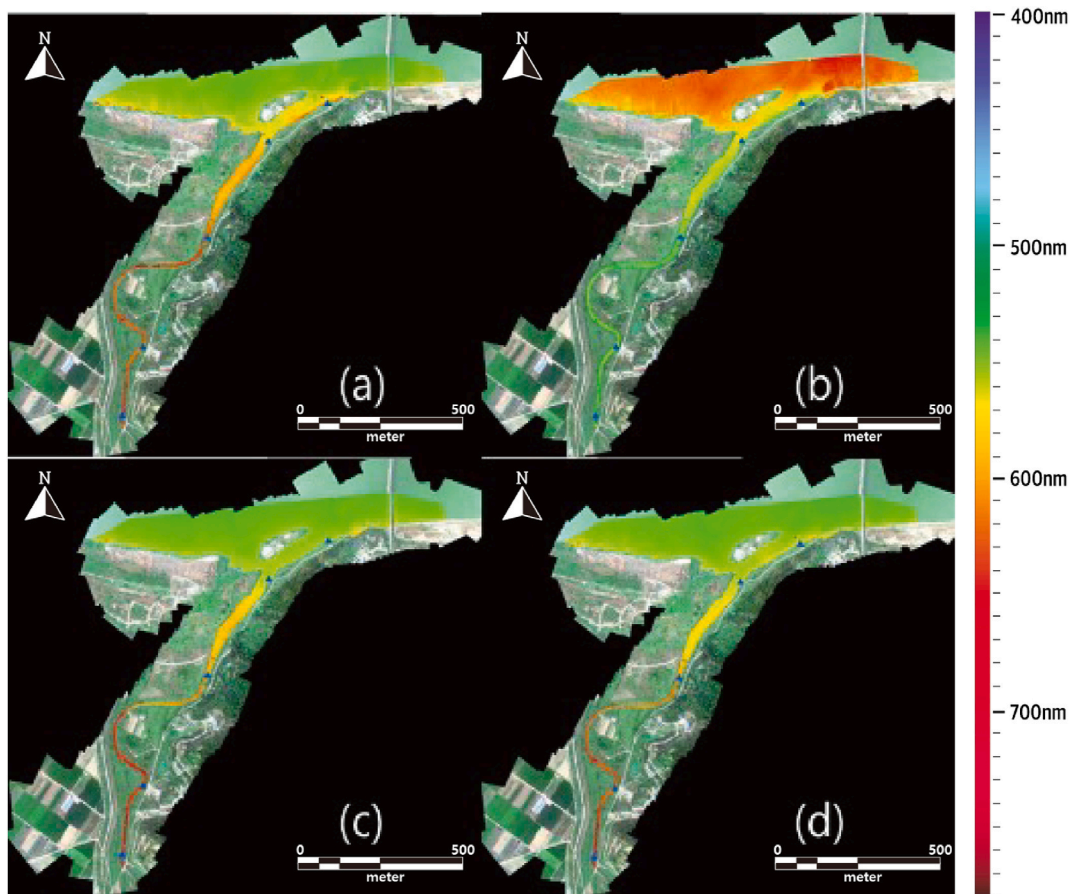


Fig. 5. Image processing in September (a) NDREI, (b) NDVI, (c) GNDVI (d) BNDVI.

**Table 4**  
Value index (NDVI, GNDVI, BNDVI, NDREI) and phycocyanin concentration correlation.

	June	R <sup>2</sup>	August	R <sup>2</sup>	September	R <sup>2</sup>
NDVI	$y = 0.1604x - 0.8625$	0.3359	$y = 0.4923x + 1148.3$	0.7607	$y = 0.532x + 1168.8$	0.7773
GNDVI	$y = 0.0102x - 0.1497$	0.3071	$y = 0.1152x - 0.8765$	0.5341	$y = 0.1172x - 3.0528$	0.2665
BNDVI	$y = 0.0276x - 0.415$	0.5143	$y = 0.0109x - 0.1789$	0.2965	$y = 0.4453x + 2038.6$	0.4146
NDREI	$y = 0.5224x + 1217.2$	0.7203	$y = 0.0191x - 0.8216$	0.5734	$y = 0.1299x - 3.2361$	0.3594

data measured in August, but it was confirmed that the correlation decreased in June as 0.3071 when the green algae began to flourish and September when the distribution began to decrease due to the rainy season. Other studies have reported that GNDVI correlates to phycocyanin with 0.64 [31].

BNDVI presented correlation coefficients of 0.5143, 0.265, and 0.4146 in June, August, and September, respectively. In general, BNDVI imaging can help analyze the spatial heterogeneity and distribution of chlorophyll [32]. However, the reason why the correlation coefficient is not relatively high in this study is thought to be due to the possibility of interference by inorganic suspended matter in water because it includes the blue wavelength band.

NDREI, which is obtained considering mixing near-red and near-infrared wavelength bands, showed a relatively high correlation with 0.7203 when the phycocyanin concentration was low in June compared to other indices. It is believed that the correlation was maintained by minimizing the interference or scattering effect of green algae compared to indices which use other wavelength bands. In addition, the near-infrared wavelength band is considered necessary to prove its correlation over a longer period because the reflection of plants containing phycocyanin is a major influence factor. This is because June, when the study began, is the rainy season, so it is necessary to check all summer months when there is no rain. Table 4 shows the correlation between each vegetation index and phycocyanin. As a result, the correlation coefficient of NDREI was higher in June when algae began to flourish, and the correlation coefficient of NDVI was higher in August and September when the algal bloom intensified.

#### 4. Conclusion

To analyze the value of the correlation between phycocyanin and spectral indices using UAVs, in-situ analysis was performed in the target waters, along with UAVs measurement. In this study, research was conducted every 10 days in June, August, and September 2021 in some areas of the Sincheon River in the Nakdong River Basin located in Changwon-gun, Gyeongsangnam-do, Korea. As a result of NDVI, GNDVI, BNDVI, and NDREI, the correlation between NDVI and phycocyanin was 0.7607 and 0.7773 in August and September, respectively, when algae were active. And the  $R^2$  between NDREI and phycocyanin was 0.7203 in June when algal bloom occurred. Therefore, we confirmed the applicability in cyanobacteria monitoring by using UAVs multispectral sensor images, considering distribution of algae, rainy season, temperature, and vegetation of the field. The correlation between index values of NDVI, GNDVI, BNDVI, and NDREI and phycocyanin concentration is selectively applied as a complementary factor to increase reliability between image data and water quality data. Based on the results obtained from this study, besides monitoring the turbidity and depth of water through sensors attached to UAVs, it is possible to easily measure and judge the distribution status of cyanobacteria and microcystin. In addition, one direction for future cyanobacteria monitoring techniques was shown.

#### Author contribution statement

Byeongwook Choi: Performed the experiments; Wrote the paper. Jaemin Lee: Analyzed and interpreted the data. Baesung Park: Contributed reagents, materials, analysis tools or data. Sungjong Lee: Conceived and designed the experiments.

#### Data availability statement

Data included in article/supplementary material/referenced in article.

#### Additional information

No additional information is available for this paper.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Sung jong, Lee reports financial support was provided by Korea Environmental Industry and Technology Institute.

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