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SPATIAL PERSISTENCE AND INTERANNUAL VARIABILITY OF FLOATING ALGAE IN KAINJI LAKE (NIGERIA): INSIGHTS FROM MULTI-YEAR SENTINEL-2 OBSERVATIONS

Osasere Omoruyi[1*], Ruby Asunomeh[1]
[1]Department of Plant Sciences and Biotechnology, Faculty of Life Sciences, Ambrose Alli University, Ekpoma, Nigeria
*Corresponding email: osasere.omoruyi@aauekpoma.edu.ng

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Background: Floating algae are increasingly recognized as indicators of ecological change in freshwater ecosystems. Although satellite remote sensing has been widely applied to monitor algal dynamics, little is known about the long-term spatial organization of floating algae in large tropical reservoirs in West Africa. **Objectives:** This study investigated the spatio-temporal dynamics of floating algae in Kainji Lake, Nigeria, from 2020 to 2025, with the aim of identifying recurrent hotspot zones, assessing interannual variability, and evaluating the long-term stability of floating algae distribution. **Methods:** Sentinel-2 Level-2A Surface Reflectance imagery was processed within the Google Earth Engine platform. Images with less than 10% cloud cover were selected and subjected to cloud masking and water extraction procedures. Floating algae were mapped using the Floating Algae Index (FAI), calculated from the red, near-infrared, and short-wave infrared spectral bands. Annual median FAI composites were generated for each year from 2020 to 2025. Descriptive statistics of positive FAI values were calculated to assess temporal variability. Multi-year persistence analysis was then performed to identify recurrent floating algae hotspot zones. **Results:** The results revealed pronounced spatial heterogeneity in floating algae occurrence across Kainji Lake. Floating algae were consistently concentrated within shoreline and embayment environments, whereas most open-water areas exhibited comparatively low occurrence. Mean annual positive FAI values ranged from 0.0656 to 0.0841, indicating interannual variability in floating algae intensity. Annual bloom extent varied from 139.93 to 168.64 km², representing 12–15% of the lake surface, with the largest coverage recorded in 2022 and the smallest in 2025. Despite these temporal fluctuations, recurrent hotspot zones remained spatially consistent throughout the study period. **Conclusion:** Floating algae in Kainji Lake exhibit persistent spatial organization rather than random distribution. This study provides the first multi-year evidence of recurrent floating algae hotspot zones in the reservoir, establishing an important baseline for understanding floating algae dynamics, thereby addressing a significant knowledge gap in West African reservoir ecosystems and providing a foundation for future ecological assessments and monitoring programmes.

Keywords: multi-year persistence; floating algae; interannual variability; Sentinel-2; remote sensing; aquatic ecosystems; Kainji Lake; Nigeria.

INTRODUCTION

Lakes are among the most valuable freshwater ecosystems because they provide drinking water, support agricultural activities, protect aquatic biodiversity, and provide a wide range of socio-economic benefits. However, these valuable ecosystems are increasingly threatened by anthropogenic activities and climate change, which have accelerated eutrophication in many lakes worldwide (Le et al., 2010; Chen et al., 2020; Janssen et al., 2019; Woolway et al., 2020; Saygi et al., 2025). With the combined effects of intensified anthropogenic activities and climate change, eutrophication and harmful algal blooms have become widespread across different lakes globally (Beusen et al., 2016; Huisman et al., 2018; Ho et al., 2019; Song et al., 2021).

Eutrophication occurs when excessive amounts of nutrients, particularly nitrogen and phosphorus, enter lakes through agricultural runoff, urban discharge, and other anthropogenic activities. These nutrients stimulate excessive algal growth, resulting in algal blooms that reduce water quality, alter water colour and odour, decrease dissolved oxygen levels, and disrupt the normal functioning of aquatic ecosystems (Khalili et al., 2025; Saygi et al., 2025). The accumulation of floating algae on the water surface also reduces light penetration into the water bodies, affecting the growth of aquatic plants and phytoplankton while threatening aquatic organisms (Guo et al., 2007; Huisman et al., 2018). In severe cases, certain algae species produce toxins such as Microcystin, which pose serious risks to drinking water supplies, aquatic biodiversity, livestock, wildlife, and human health (Chorus & Welker, 2021; Hayes et al., 2020).

Since algal blooms pose significant threats to freshwater biodiversity and water resources, regular monitoring of their spatial and temporal distribution is therefore essential for sustainable lake management and environmental protection (Rolim et al., 2023; Colkesen et al., 2024). Kainji Lake which is one of the largest man-made lakes in Africa serves as an important source of hydroelectric power generation, fisheries, irrigation, domestic water supply, and biodiversity conservation. It also supports thousands of people living in surrounding communities whose livelihoods depend largely on fishing, farming, and livestock production (Omojowo et al., 2010; Ehigiator et al., 2017; Umar et al., 2024). Despite its ecological and economic importance, increasing human activities within the lake, in addition to climate change, may encourage the development of algae, thereby affecting water quality and ecosystem health (Ma et al., 2023; Xue et al., 2026). Continuous monitoring of algae is therefore necessary in this lake, as it will help us track the changes occurring within it and support the effective management of this important freshwater resource.

The traditional algae monitoring techniques mainly consist of field observation and laboratory analysis (Gregor & Maršálek, 2004; Ayeni & Adesalu, 2018). These methods provide accurate information at specific sampling locations, but are often expensive, labour intensive and time consuming and are therefore not suitable for continuous monitoring of large water bodies. Furthermore, the spatial and temporal variability of algal blooms makes it difficult to adequately characterize their distribution using in situ measurements alone. As a result, satellite remote sensing has become an effective and practical alternative for monitoring algae blooms in surface water bodies such as lakes, as it provides fast, repetitive, and cost-effective observations over large areas (Hill et al., 2020).

Several remote sensing approaches have been developed for algal bloom detection, including band ratio techniques, spectral indices, machine learning, and deep learning methods (Park et al., 2024; Wang & Qin, 2025). Among these approaches, spectral indices remain widely used because they are simple to implement, computationally efficient, and require minimal input data compared with machine learning algorithms, which often require extensive training samples and parameter optimization. One of the most widely used spectral indices is the Floating Algae Index (FAI), developed by Hu (2009), which utilizes the spectral characteristics of the red, near-infrared, and short-wave infrared bands to distinguish floating algae from surrounding water. Compared with traditional vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), the FAI is less sensitive to atmospheric effects and has demonstrated reliable performance in detecting floating algae (Hu, 2009; Liu et al., 2021).

Ocean-colour sensors such as the Moderate Resolution Imaging Spectroradiometer, Medium Resolution Imaging Spectrometer, and Ocean and Land Colour Instrument have been widely used for monitoring algal blooms in large water bodies because of their frequent revisit periods and good spectral characteristics (Hu, 2009; Xing & Hu, 2016; Binding et al., 2013; Qi et al., 2020). However, their relatively coarse spatial resolution limits their application in many inland water bodies, particularly smaller lakes where detailed spatial information is required (Kutser et al., 2004; Downing et al., 2006; Olmanson et al., 2011). Landsat imagery has also been used for algae monitoring, but its revisit interval is often insufficient to capture the rapid day to day variations in floating algae (Ho et al., 2017; Zhao et al., 2018; Qi et al., 2018; Feng et al., 2021). The launch of Sentinel-2 MultiSpectral Instrument (MSI) has significantly improved inland water monitoring because its 10 m spatial resolution and five-day revisit period provide detailed and frequent observations of freshwater ecosystems making Sentinel-2 particularly suitable for monitoring water quality, phytoplankton, chlorophyll-a, turbidity, and floating algae in inland waters (Ruddick et al., 2016; Pahlevan et al., 2019; Kuhn et al., 2019; Cao et al., 2019; Kravitz et al., 2021).

Despite growing global concern regarding algal blooms and the increasing use of satellite remote sensing for aquatic ecosystem monitoring, important knowledge gaps remain regarding the spatial organization and temporal persistence of floating algae in large tropical reservoirs of West Africa. Existing studies in Kainji Lake have primarily focused on fisheries, hydrology, and reservoir management, whereas the spatial ecology of floating algae has received little attention. Consequently, it remains unclear whether floating algae in Kainji Lake occur randomly across the reservoir or whether specific areas consistently function as accumulation hotspots over time.

Addressing this knowledge gap is important because persistent algae accumulation zones may indicate underlying environmental controls associated with reservoir morphology, hydrodynamics, and shoreline processes. Identifying such recurring spatial patterns is essential for understanding ecosystem functioning and for supporting targeted environmental monitoring and management interventions.

This study was guided by the hypothesis that floating algae in Kainji Lake are not randomly distributed but exhibit persistent spatial heterogeneity, with shoreline and embayment environments functioning as recurrent accumulation zones despite interannual fluctuations in algal intensity. It was further hypothesized that multi-year satellite observations would reveal stable spatial patterns that may not be evident from short-term assessments.

Therefore, the aim of this study was to determine the spatial persistence and interannual variability of floating algae in Kainji Lake between 2020 and 2025 using Sentinel-2 imagery and the Floating Algae Index (FAI) within the Google Earth Engine (GEE) platform. Specifically, the study sought to determine whether persistent spatial hotspots of floating algae exist within the reservoir, characterize their interannual variability, and evaluate the extent to which these distribution patterns remain stable over time. By addressing these objectives, this study provides new evidence on the spatial persistence of floating-algae accumulation in Kainji Lake and establishes a baseline understanding of their recent multi-year dynamics in one of West Africa's major tropical reservoirs.

MATERIALS AND METHODS

Study area

The study was conducted in Kainji Lake (Figure 1), one of the largest artificial reservoirs in Africa and the largest reservoir in Nigeria. The lake was formed in 1968 following the construction of the Kainji Dam on the Niger River primarily for hydroelectric power generation. It is located in north-central Nigeria between approximately 9°50′N and 10°57′N latitude and 4°20′E and 4°50′E longitude, extending across Niger and Kebbi States. With its large surface area, complex shoreline configuration, and diverse hydrological environments, Kainji Lake represents an important tropical reservoir system for investigating the spatial dynamics of floating algae.

Beyond its role in energy production, Kainji Lake supports multiple ecosystem services, including fisheries, irrigation, domestic water supply, and biodiversity conservation.

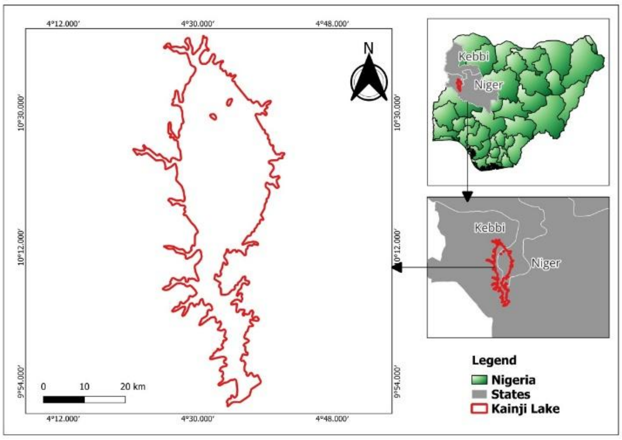

Figure 1. Study area (Kainji Lake)

The reservoir provides habitat for diverse aquatic organisms, including fish communities and aquatic vegetation, while supporting the livelihoods of thousands of surrounding residents whose activities depend largely on fishing, agriculture, and livestock production (Samuel et al., 2010; Ehigiator et al., 2017; Umar et al., 2024).

The morphological characteristics of Kainji Lake are particularly relevant for the spatial distribution of floating algae. The reservoir contains extensive shallow littoral zones, shoreline margins, and semi-enclosed embayment environments that differ from the open-water regions in terms of water circulation, sediment accumulation, and nutrient retention. Such nearshore environments may provide favourable conditions for the accumulation and persistence of floating algal material due to reduced water movement and localized nutrient enrichment. Consequently, the lake provides an appropriate natural environment for assessing whether floating algae exhibit persistent spatial organization rather than random distribution across the reservoir.

Given the ecological importance of Kainji Lake and the limited understanding of the long-term spatial behaviour of floating algae within tropical African reservoirs, this study used the lake as a case study to investigate multi-year patterns of floating algae distribution and identify areas of recurrent accumulation using satellite-based observations.

Data acquisition and processing

All satellite data processing and analysis were performed using the GEE cloud-computing platform, which provides access to large-scale geospatial datasets and enables reproducible processing of multi-temporal satellite observations (Velastegui-Montoya et al., 2023). The analysis was based on Sentinel-2 MultiSpectral Instrument (MSI) Level-2A Surface Reflectance products available through the GEE data catalogue. The study period covered six consecutive years from January 2020 to December 2025, allowing the assessment of both interannual variability and persistent spatial patterns of floating algae distribution.

Sentinel-2 MSI imagery was selected because of its combination of high spatial resolution, spectral capabilities, and frequent revisit interval. The mission provides 10 m spatial resolution in the visible and near-infrared bands and a nominal revisit frequency of approximately five days, enabling the detection and monitoring of floating algal features in inland water systems (Colkesen et al., 2024). Sentinel-2 Level-2A products were used because they provide atmospherically corrected surface reflectance data, which are more suitable for quantitative analysis of water surface spectral characteristics compared with top-of-atmosphere reflectance products (De Petris et al., 2023).

The Sentinel-2 image collection was filtered spatially using the boundary of Kainji Lake and temporally using the study period (2020–2025). To minimize the influence of atmospheric contamination, only scenes with a scene-level cloud cover of less than 10% (CLOUDY_PIXEL_PERCENTAGE < 10) were retained. Cloud and cirrus contamination were subsequently removed using the Sentinel-2 quality assessment band (QA60). This procedure was applied to minimize reflectance contamination from clouds and cloud shadows, which can substantially affect the accuracy and uncertainty of remotely sensed water-quality estimates in inland waters (Pahlevan, 2021; Singh et al., 2025).

Following cloud masking, Sentinel-2 reflectance values were converted to surface reflectance values by applying the standard scaling factor of 0.0001 (division by 10,000), as recommended for Sentinel-2 Level-2A products (Muzhoffar et al., 2023). This conversion ensures that spectral reflectance values are expressed as physically meaningful quantities suitable for subsequent spectral index calculations.

To restrict the analysis exclusively to the water surface of Kainji Lake, a water mask was generated using the Normalized Difference Water Index (NDWI). The NDWI was calculated from Sentinel-2 Green (Band 3) and near-infrared (Band 8) reflectance using the normalized difference formulation (McFeeters, 1996). Pixels with NDWI > 0.05 were classified as water pixels, while non-water pixels were excluded from subsequent FAI calculations. The threshold of 0.05 was adopted as a conservative threshold to reduce the inclusion of mixed land–water pixels along the shoreline.

After pre-processing, the final cloud-free water-only Sentinel-2 observations were used for the calculation of the FAI and subsequent analysis of annual floating algae distribution patterns. The complete processing workflow, including data acquisition, atmospheric correction, cloud masking, water extraction, FAI calculation, and annual composite generation, was implemented within the GEE environment (Figure 2).

Calculation of the FAI

The FAI was calculated from Sentinel-2 surface reflectance data to identify the spatial distribution of floating algal accumulations within Kainji Lake. The FAI approach is based on the spectral characteristics of floating algae, which exhibit increased reflectance in the near-infrared (NIR) region compared with surrounding water surfaces. By using a baseline interpolation between the red and short-wave infrared (SWIR) wavelengths, FAI enhances the spectral contrast associated with floating algal materials while reducing the influence of variations in water colour and atmospheric effects (Hu, 2009).

For Sentinel-2 MSI imagery, FAI was calculated using the red (Band 4), near-infrared (Band 8), and short-wave infrared (Band 11) bands according to Equation (1):

$$\mathrm{FAI} = \mathrm{R_{NIR}} - \left[\mathrm{R_{RED}} + (\mathrm{R_{SWIR}} - \mathrm{R_{RED}}) \times \frac{\lambda_{NIR} - \lambda_{RED}}{\lambda_{SWIR} - \lambda_{RED}}\right], \quad (1)$$

where R_{NIR} represents the surface reflectance of the near-infrared band (Band 8); R_{RED} represents the surface reflectance of the red band (Band 4); R_{SWIR} represents the surface reflectance of the short-wave infrared band (Band 11).

The corresponding central wavelengths used in the calculation were λ_{RED} = 665 nm (Band 4); λ_{NIR} = 842 nm (Band 8); λ_{SWIR} = 1610 nm (Band 11).

The selection of these spectral bands follows previous applications of FAI for detecting floating algae and cyanobacterial accumulations in inland waters using multispectral satellite observations (Hu, 2009; Pu et al., 2022; Muzhoffar et al., 2023; Huang et al., 2026). The FAI is particularly suitable for floating algae detection because it exploits the strong NIR reflectance signal of surface-floating vegetation and algae while minimizing the effects associated with water turbidity and atmospheric variability.

In this study, positive FAI values were interpreted as indicating the presence of floating algal materials, whereas negative or near-zero values represented predominantly open-water conditions with limited floating algae occurrence (Hu, 2009; Pu et al., 2022). The calculated FAI layers were subsequently used for annual composite generation and spatial analysis of floating algae persistence and interannual variability across Kainji Lake.

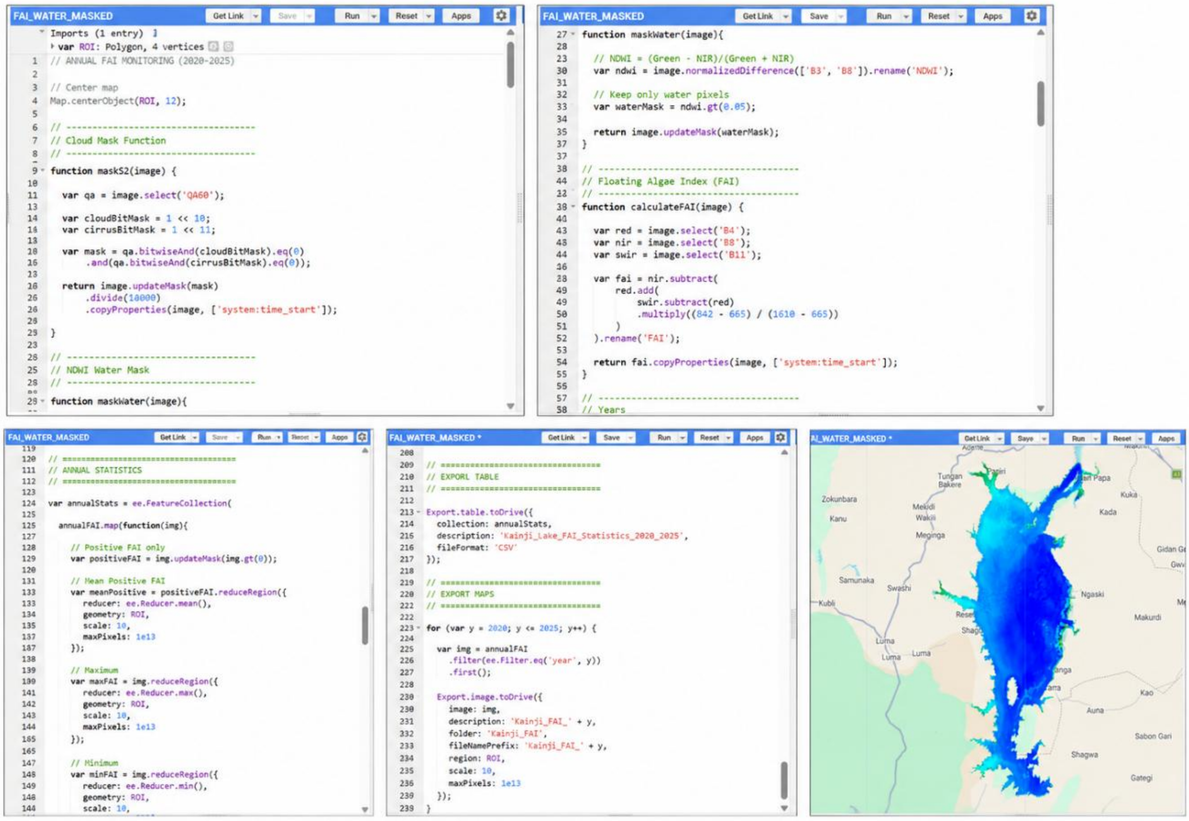

Figure 2. GEE workflow for Sentinel-2 pre-processing and floating algae mapping

Generation of annual FAI composites and identification of persistent floating algae hotspots

To characterize interannual patterns of floating algae distribution, annual FAI composite images were generated for each year of the study period (2020–2025). All available cloud-masked Sentinel-2 observations within each calendar year were combined using a median compositing approach. The median reducer was selected because it minimizes the influence of residual atmospheric effects, cloud-related artefacts, and short-term extreme observations, while providing a representative estimate of annual surface conditions (Gorelick et al., 2017).

The annual FAI composites were clipped to the boundary of Kainji Lake and subsequently exported from GEE for cartographic visualization and further spatial analysis in ArcGIS 10.7.1. The annual maps were displayed using a continuous colour scale, where lower or negative FAI values represented predominantly open-water conditions, whereas higher positive FAI values indicated increased occurrence of floating algal materials.

To identify areas characterized by persistent floating algae occurrence, annual FAI maps were analysed collectively rather than independently. Pixels exhibiting positive FAI values (FAI > 0) were classified as floating algae occurrence pixels for each year. A multi-year persistence layer was then generated by calculating the frequency with which each pixel was classified as positive FAI during the six-year study period. The resulting persistence metric represents the proportion of years in which a given location exhibited detectable floating algae signals.

The persistence value for each pixel was calculated as:

$$\text{Persistence}(\%) = \frac{N_{\text{positive}}}{N_{\text{total}}} \times 100, \tag{2}$$

where N_{positive} represents the number of years in which a pixel showed positive FAI values; N_{total} represents the total number of analysed years (six years).

Based on the persistence layer, areas with consistently high occurrence frequency were classified as persistent floating algae hotspots. The hotspot classification threshold was defined as ≥ 50% of study years. These persistent hotspot zones were subsequently used to evaluate the spatial stability of floating algae distribution within Kainji Lake and to support the assessment of the study hypothesis regarding non-random spatial organization of floating algae.

Annual FAI statistical analysis and assessment of interannual variability

To quantify temporal variations in floating algae occurrence, annual FAI statistics were calculated for each year of the study period (2020–2025). Statistical analyses were performed using only pixels with positive FAI values (FAI > 0), as positive FAI responses are generally associated with the presence of floating algal materials (Hu, 2009; Pu et al., 2022). Excluding non-algal water pixels allowed the analysis to focus on the spatial and temporal characteristics of detected floating algae rather than background water conditions.

For each year, descriptive statistics including the mean, minimum, maximum, and standard deviation (SD) of FAI values were calculated. The annual mean FAI was used as an indicator of the average spectral response across the analysed lake surface, while maximum FAI values represented the highest detected spectral response. Minimum FAI values described the lower range of the observed FAI distribution, whereas the standard deviation was used to characterize spatial variability in FAI values across the lake surface.

To evaluate interannual variability, annual FAI statistics were compared across the six-year observation period. Changes in mean and maximum FAI values were interpreted as differences in the overall magnitude and spatial variability of the FAI signal, whereas changes in standard deviation reflected differences in the heterogeneity of FAI values across the lake surface.

To evaluate interannual variability, annual statistics were compared across the six-year observation period. Changes in mean and maximum FAI values were interpreted as variations in the overall intensity and magnitude of floating algae occurrence, whereas changes in standard deviation reflected differences in spatial heterogeneity across the lake surface.

Study limitations

This study has several limitations. First, the absence of concurrent field measurements prevented direct validation of the satellite-derived FAI; thus, the results should be interpreted as indicators of the relative spatial and temporal distribution of floating algae. Second, seasonal dynamics were not assessed because persistent cloud cover during the rainy season limited the availability of cloud-free Sentinel-2 imagery, making consistent seasonal comparisons impractical. Third, the study focused on the spatio-temporal distribution and persistence of floating algae and did not assess environmental drivers such as precipitation, temperature, nutrient inputs, land use, or hydrological conditions. Future studies combining field observations, higher-frequency satellite data, and environmental datasets could provide a more comprehensive understanding of the mechanisms controlling floating algae dynamics in Kainji Lake.

RESULTS

Interannual variability of floating algae intensity

Annual descriptive statistics derived from the Floating Algae Index (FAI) revealed clear interannual variability in floating algae intensity within the study area between 2020 and 2025 (Table 1). Mean positive FAI values ranged from 0.0656 in 2023 to 0.0841 in 2024, indicating temporal fluctuations in the average intensity of floating algae accumulation over the study period. Although mean FAI values declined gradually from 0.0770 in 2020 to 0.0656 in 2023, they increased markedly in 2024 (0.0841) and remained relatively high in 2025 (0.0833).

Maximum FAI values also exhibited annual variability, with the highest value (0.4496) recorded in 2023, closely followed by 0.4495 in 2025, while the lowest maximum value (0.4045) was observed in 2022. Minimum FAI values ranged from −0.1028 in 2025 to −0.0776 in 2023, reflecting persistent areas of low or negative FAI values across the study period. The annual standard deviation varied between 0.0491 in 2023 and 0.0689 in 2024, suggesting that the spatial variability of floating algae distribution was lowest in 2023 and highest in 2024.

Table 1. Annual descriptive statistics of FAI values in Kainji Lake (2020–2025)

Year	Mean	Min	Max	SD
2020	0.0770	–0.0965	0.4167	0.0638
2021	0.0690	–0.0919	0.4129	0.0612
2022	0.0684	–0.0838	0.4045	0.0545
2023	0.0656	–0.0776	0.4496	0.0491
2024	0.0841	–0.1022	0.4397	0.0689
2025	0.0833	–0.1028	0.4495	0.0672

Overall, the descriptive statistics indicate that floating algae were detected throughout the study period, although their intensity and spatial variability differed among years. The relatively higher mean positive FAI and standard deviation observed in 2024 and 2025 suggest increased algae accumulation and greater spatial heterogeneity during these years compared with the earlier part of the study period. Detailed annual statistical summaries are presented in Table 1.

Spatial distribution of floating algae (2020–2025)

Figures 3a–f illustrate the spatial distribution of floating algae in Kainji Lake from 2020 to 2025. In 2020 (Figure 3a), floating algae can be seen around the lake's shores and its embayment. The maximum FAI value reported this year was 0.417, while the minimum value was –0.097. The central area of the lake was dominated by low values, indicating clean surface water.

The enlarged portion indicated vast patches of moderate to high floating algae around the lake's border, especially in shallow places where intense water movement may likely be minimized. For 2021 (Figure 3b), the maximum FAI value recorded this year dropped to 0.4129, while the minimum was –0.092. The spatial pattern of floating algae is similar to 2020. The enlarged map clearly reveals areas of algae spread over a larger area, particularly in the lake's eastern side where several patches of moderate to high FAI values emerged. The spatial distribution of 2022 (Figure 3c) was also similar to those of the previous years. The minimum and maximum FAI values recorded were –0.072 and 0.4045, respectively. The enlarged image shows that high floating algae was also present along the lake's edge in the southern region, while much of the open water still remained free from floating algae.

Although 2023 (Figure 3d) recorded the highest maximum FAI, the highest mean positive FAI occurred in 2024. Similar to previous years, high floating algae were clustered near the lake's shoreline and embayment zones, whereas the central part remained clear. The enlarged portion revealed broad regions of yellow and orange, indicating a lower algal presence in that region compared to 2020. The maximum FAI value recorded for this year was 0.450, the highest reported during the study period, while the minimum value was –0.0776. This indicates the presence of localized areas with increased floating algae. In 2024 (Figure 3e) the maximum FAI value remained high at 0.440, while the minimum value decreased to –0.1022. Floating algae were concentrated around shoreline zones while several scattered hotspots were visible in the eastern part of the lake. However, the enlarged section showed that the distribution pattern slightly changed compared to 2021 with the same region that showed high floating algae intensity in 2021 now showing low intensity in 2024. The spatial pattern of floating algae in 2025 (Figure 3f) is similar to that of 2024. The maximum FAI value recorded in 2025 was 0.4495, while the minimum value was –0.1028. The enlarged image revealed zones of high FAI values concentrated near the shoreline to the south, while the majority of the lake surface continued to exhibit low FAI values.

To further quantify the observed spatial patterns, the annual extent of floating algae was estimated for each year (Table 2). The results revealed clear interannual variability in algae coverage across the lake between 2020 and 2025. The recorded bloom area ranged from 139.93 km² (12.06% of the lake surface) in 2025 to 168.64 km² (14.54%) in 2022, representing the lowest and highest values observed during the study period, respectively. Intermediate values were recorded in 2021 (155.99 km²; 13.45%), 2020 (153.26 km²; 13.21%), 2023 (149.54 km²; 12.89%), and 2024 (141.63 km²; 12.21%). Overall, floating algae occupied approximately 12–15% of the lake surface annually, with a general decline in bloom extent after the peak observed in 2022.

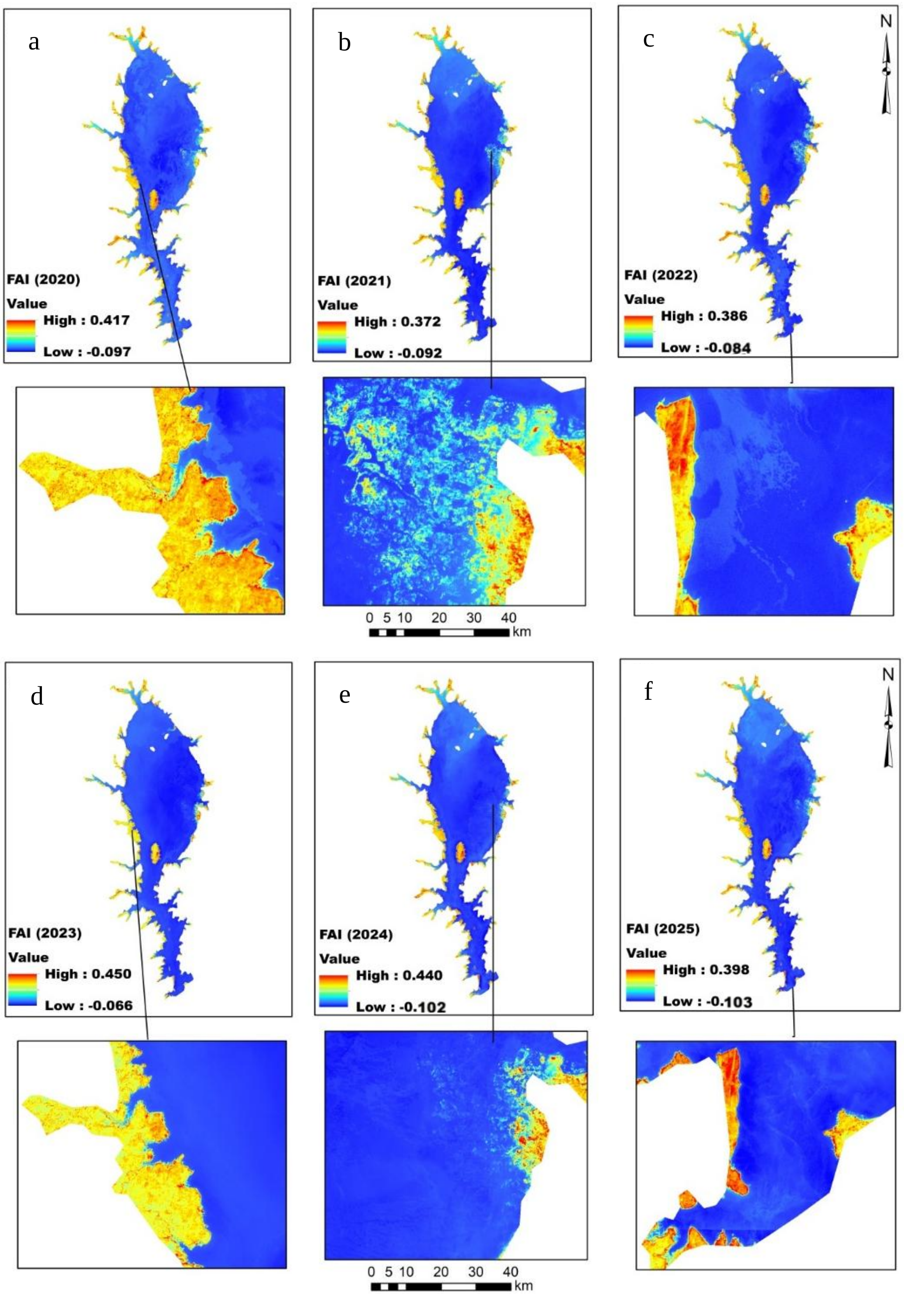

Figure 3. Spatial distribution of FAI values in Kainji Lake from 2020 to 2025: a – 2020, b – 2021, c – 2022, d – 2023, e – 2024, f – 2025. Insets beneath each panel provide enlarged views of selected regions, highlighting localized areas of FAI that may not be readily discernible at the full spatial scale

Table 2. Annual floating algae coverage in Kainji Lake (2020–2025)

Year	Bloom area, km²	% of Lake surface
2020	153.26	13.21
2021	155.99	13.45
2022	168.64	14.54
2023	149.54	12.89
2024	141.63	12.21
2025	139.93	12.06

These quantitative estimates are consistent with the spatial patterns shown in Figures 3a–f, confirming that floating algae occurrence was concentrated within specific portions of the reservoir rather than being uniformly distributed across the lake. The persistence of localized bloom areas across all years suggests that certain sections of the reservoir consistently provide environmental conditions favourable for floating algae accumulation.

Persistence of floating algae hotspots

The persistence map (Figure 4) shows that recurrent floating algal signals were spatially concentrated within specific parts of the

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reservoir. Recurrent hotspot areas were primarily concentrated along reservoir margins and within relatively sheltered sections of the lake, whereas much of the open-water area showed lower persistence. Although the overall intensity and extent of the FAI signal varied among years, the locations of recurrent hotspot areas remained consistent throughout the study period.

The spatial distribution of hotspot zones indicates that positive FAI signals repeatedly occurred in specific parts of the reservoir rather than being uniformly distributed across the lake surface. The recurrence of these areas across multiple years indicates a degree of spatial persistence in the observed FAI signal.

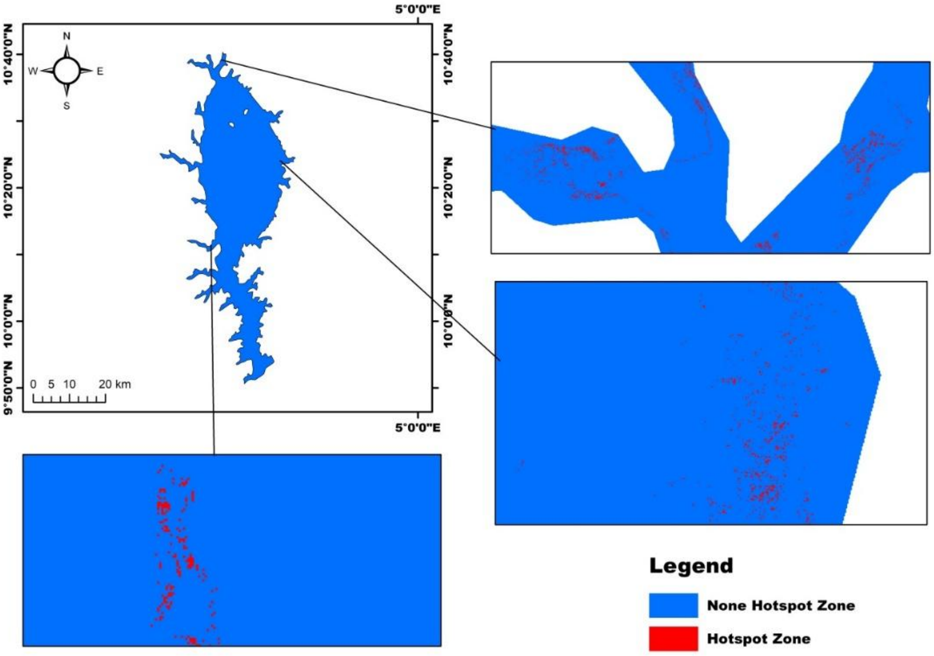

Figure 4. Multi-year persistence map showing recurrent floating algae hotspot zones (red) and non-hotspot areas (blue)

DISCUSSION

Evidence for persistent spatial organization of floating algae

The results indicate pronounced spatial heterogeneity in the distribution of positive FAI signals in Kainji Lake. Recurrent signals were concentrated primarily along shoreline environments and within embayment zones, while much of the open-water area showed lower FAI persistence. The persistence analysis further indicates that several locations repeatedly exhibited positive FAI signals across the study period.

This finding supports the primary hypothesis of the study and suggests that specific environmental settings within the reservoir consistently favour the accumulation and retention of floating algae. The observed hotspot zones likely reflect the combined influence of nutrient availability, water residence time, and local hydrodynamic conditions rather than random bloom development alone.

Shoreline environments are generally shallower than open-water areas and frequently receive nutrient inputs from surrounding catchments through river inflows, surface runoff, agricultural activities, livestock production, and nearby human settlements. Nutrient enrichment, particularly involving nitrogen and phosphorus, is widely recognized as a key factor promoting algal growth when favourable environmental conditions exist (Huisman et al., 2018; Khalili & Moridi, 2025). The recurrent concentration of floating algae along the shoreline of Kainji Lake is therefore consistent with the established relationship between catchment-derived nutrient inputs and algal proliferation reported in freshwater ecosystems worldwide (Beusen et al., 2016; Janssen et al., 2019).

Embayment environments also emerged as persistent hotspot zones throughout the study period. Compared with open-water regions, embayments typically experience reduced water circulation and more limited water exchange (Woodward et al., 2017). These conditions increase water residence time and create opportunities for both nutrient retention and the accumulation of floating biomass. Similar spatial patterns have been reported in other freshwater ecosystems where sheltered bays and semi-enclosed environments consistently support greater algal accumulation than highly mixed open-water regions (Qi et al., 2018; Song et al., 2021). The persistence of hotspot zones in Kainji Lake therefore highlights the importance of reservoir morphology and hydrodynamic processes in shaping the spatial ecology of floating algae.

In contrast, the central open-water portions of the reservoir generally exhibited lower FAI values and reduced persistence. This pattern may be associated with stronger circulation, larger fetch, and enhanced wind-driven mixing, all of which contribute to the dispersion of floating material and reduce the likelihood of long-term surface accumulation (Paerl et al., 2016). Similar hydrodynamic controls on floating algae distribution have been documented in both lakes and reservoirs worldwide (Hu, 2009; Huisman et al., 2018).

Interannual variability and stability of hotspot patterns

Although the intensity of floating algae occurrence varied among years, the overall spatial configuration of hotspot zones remained relatively stable throughout the study period. This observation supports the second hypothesis of the study and demonstrates the value of multi-year satellite observations for identifying persistent ecological patterns that may not be evident from short-term assessments.

The annual variability observed in FAI statistics suggests that floating algae responded to changing environmental conditions over time. Variations in rainfall, runoff, water-level fluctuations, water residence time, nutrient loading, and meteorological conditions have all been identified as important drivers of algal bloom dynamics in freshwater ecosystems (Huisman et al., 2018; Janssen et al., 2019; Woolway et al., 2020; Song et al., 2021). Consequently, year-to-year differences in floating algae intensity likely reflect temporal variability in these environmental controls.

Despite these fluctuations, the persistence analysis revealed that hotspot locations remained broadly consistent over time. This distinction between temporal variability in bloom intensity and spatial stability in bloom location is an important ecological finding. It suggests that while environmental conditions may influence the magnitude of floating algae occurrence in a given year, the underlying spatial controls governing accumulation remain relatively constant. Consequently, recurrent hotspot zones may represent areas where physical and ecological conditions repeatedly favour floating algae retention.

Higher mean positive FAI values observed in 2020, 2024, and 2025 than in the intervening years may indicate periods during which environmental conditions became more favourable for floating algae proliferation. However, because environmental variables were not directly incorporated into the present analysis, the mechanisms responsible for these fluctuations require further investigation.

Comparison with previous studies and implications for monitoring

The spatial patterns identified in Kainji Lake are consistent with observations reported for other freshwater ecosystems. Studies conducted in Lake Erie, Lake Dianchi, and several other lakes have similarly documented the tendency for floating algae accumulations to occur preferentially within nearshore and sheltered environments rather than being uniformly distributed across entire water bodies (Ho et al., 2017; Zhao et al., 2018; Pu et al., 2022; Colkesen et al., 2024). The agreement between these studies and the present findings suggests that common physical and ecological processes may govern floating algae accumulation across geographically distinct aquatic systems.

From a management perspective, the identification of persistent hotspot zones provides valuable information for environmental monitoring and reservoir management. Because shoreline and embayment environments repeatedly exhibited elevated occurrence of floating algae, these areas represent logical priorities for routine surveillance and targeted field sampling. Concentrating monitoring efforts within recurrent hotspot zones may improve the efficiency of bloom detection and support earlier management responses to increasing algal abundance.

Furthermore, the results demonstrate the utility of satellite-based observations for identifying long-term spatial patterns in large tropical reservoirs where regular field monitoring may be logistically challenging. The persistence framework developed in this study provides a baseline for future investigations and may support the development of spatially targeted management strategies aimed at reducing nutrient inputs and mitigating the ecological impacts associated with floating algae accumulation.

Overall, the study demonstrates that floating algae in Kainji Lake exhibit both interannual variability and pronounced spatial persistence. While algal intensity fluctuated among years, recurrent hotspot zones remained identifiable throughout the study period, highlighting the importance of spatially explicit approaches for understanding and managing floating algae dynamics in tropical reservoir systems.

CONCLUSION

The results of this study demonstrate that floating algae in Kainji Lake exhibit pronounced spatial heterogeneity and are not randomly distributed across the reservoir. Persistent accumulation zones were consistently concentrated within shoreline and embayment environments, whereas much of the open-water region showed comparatively low occurrence and low persistence of floating algae. These findings support the hypothesis that specific areas of the reservoir function as recurrent floating algae hotspots over time.

Although the intensity of floating algae occurrence varied among years, the overall spatial configuration of hotspot zones remained relatively stable throughout the 2020–2025 study period. This finding supports the hypothesis that multi-year satellite observations can reveal persistent spatial patterns that may not be evident from short-term assessments. The observed distinction between temporal variability in algal intensity and long-term stability in hotspot location highlights the importance of considering both spatial and temporal dimensions when evaluating floating algae dynamics.

The principal contribution of this study is the identification and characterization of persistent floating algae hotspot zones within Kainji Lake using multi-year Sentinel-2 observations and persistence-based spatial analysis. While previous studies in the reservoir have largely focused on hydrology, fisheries, and reservoir management, information on the long-term spatial organization of floating algae has remained limited. By documenting recurrent accumulation areas and their interannual dynamics, this study addresses an important knowledge gap regarding the spatial ecology of floating algae in one of West Africa's largest tropical reservoirs.

The results provide the first multi-year evidence that floating algae occurrence in Kainji Lake is governed by persistent spatial structures rather than by purely random annual fluctuations. This establishes a baseline for future investigations of floating algae dynamics and contributes to a broader understanding of spatial persistence in tropical reservoir ecosystems.

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Author's statements

Contributions

Conceptualization: O.O.; Data curation: all authors; Formal analysis: all authors; Investigation: all authors; Methodology: all authors; Project administration: all authors; Resources: all authors; Software: all authors; Visualization: all authors; Writing – original draft: all authors; Writing – review & editing: all authors.

Declaration of conflicting interest

The authors declare no competing interests.

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Data used for the study would be made available on request.

AI Disclosure

Generative AI tools were used solely for language editing and proofreading. The authors take full responsibility for the manuscript's content, analysis, interpretations, and conclusions.

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