41

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Using Remote-sensing Technique to Assess the Role of Common Reed [*Phragmites australis* (CAV.) Trin. Ex. Steud] in Restoring Eutrophication in Idku Wetland in Egypt

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IDKU wetland is one of Egypt's Northern Delta Lakes, which is threatened by nutrients that are discharged from the neighborhood. Aquatic macrophytes may sequester large amounts of these nutrients. Therefore, this study aims to assess the common reed (*Phragmitis australis*) role in restoring the eutrophic Idku wetland. The lake water and sediments have high N, P, Ca and K contents, which increase the risk of eutrophication. The use of GIS technique reveals that the lake water and sediments exhibit high concentrations of inorganic nutrients in areas nearest to the drain discharge. The remote-sensing technique detects that the common reed covers 1840.5ha (14.6% of the total lake area). The plant shoots produce 31.62tons ha^{-1} dry biomass with net production of 116377.23tons per lake. The plant can sequester 4.76, 16.69, 261.59, 1168.08, and 903.46tons of P, N, Ca, K, and Mg, respectively. In addition, the shoots contain 10.2% crude protein, 8.3% lipids, and 43.0% carbohydrates, yielding 459.7± 98.0Mcal kg^{-1} of gross energy. These results sufficiently demonstrate that the common reed shoots can be used as excellent fodder. Common reed shoots can potentially sequester 3.015t of carbon, whereas the rhizomes and roots store 0.838 and 0.216 tons of carbon per lake area. This study concludes that the remote-sensing technique is a good tool for estimating the coverage area of *P. australis*. Common reed plants offer high potential for treating eutrophication by improving the water and sediment quality through accumulation and translocation of inorganic nutrients in its tissues as excellent fodder. In addition, these plants help reduce global warming owing to their high potential to sequester carbon.

Keywords: Carbon sequestration, Eutrophication, Lake Idku, Nutrients, Nutritional value.

Introduction

Humans completely rely on Earth's ecosystems and ecological services for their well-being, and these services contribute to economic activity (Alprol et al., 2021). Wetlands, sometimes known as ecosystems, are extremely important to humans and biodiversity (Galal et al., 2012). Wetland goods and services provide many benefits to people, and wetland systems are the "homes" of a large variety of plants and animals and their habitats (Shaltout et al., 2017). A wide range of biosorbents formed from plant biomass can be exploited to manage water pollution and recover nutrients via adsorption (Takaya et al., 2016; Plaimart et al., 2021). Macrophytes are large aquatic plants that dominate wetland and shallow lakes (Shaltout et al., 2017), and they have been employed to reduce nutrients in home, industrial, and agricultural wastewater (Eid et al., 2010). Furthermore, they contribute to healthy ecosystems by functioning as primary providers of oxygen through photosynthesis, providing a substrate for algae and refuge for fish

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and numerous invertebrates, aiding in nutrient recycling, and offering the potential for treating wastewater (Ng & Chan, 2017).

Contamination of the aquatic environment is a primary problem that jeopardizes the survival of aquatic organisms (Abo-Taleb et al., 2020). Over the past many decades, eutrophication of lakes has become a chronic environmental issue (Ostrofsky et al., 2020). Numerous lakes worldwide are threatened by extensive eutrophication, which poses serious issues in terms of water supply, food security, and public health (Janssen et al., 2017). Agriculture is responsible for more than half of the nutrient loads carried by water in the Baltic Sea watersheds (Kiani et al., 2021). Excess nutrients tend to concentrate on lake bottoms where they are recycled back into the overlying water column (internal nutrient loading), which perpetuates the eutrophication problem (Kiani et al., 2020). Phosphorus and nitrogen inputs to lakes are typically the primary determinant of productivity and biomass accumulation, whereas other nutrients, light, and grazing also play a role (Ostrofsky et al., 2020). Removing sediments from eutrophicated shallow lakes may not only be an effective method of restoring lakes but also can recycle nutrients from the sediments in damaged coastal-nourishment areas (De Vincenzo et al., 2019). Reducing N and P leaching from nutrient-rich sediment and thus increasing the total pool of nutrients accessible to plants or microorganisms is one method of improving environmental sustainability (Kiani et al., 2021).

Wetlands are important ecosystems to consider while regulating and assessing the Earth's carbon pool because they act as a substantial carbon sink (Eid et al., 2010). They store approximately 68% of the carbon stocks in terrestrial soils (Reddy & DeLaune, 2008) and play a key role in carbon sequestration (Eid & Shaltout, 2013; Shaltout et al., 2020). Understanding the role of macrophytes in coastal carbon cycling requires an assessment of the outcome of carbon production within the system (Obrador & Pretus, 2012). A massive increase in research is urgently needed to understand carbon sequestration, particularly under Article 3.4 of the Kyoto Protocol of the United Nations Framework Convention on Climate Change, which allows countries to consider carbon sequestration to reduce greenhouse-gas emissions (IPCC, 2001). Wetlands are among the largest biological carbon stores in the world, and they play a critical role in the global carbon cycle (Chmura et al., 2003; Mitra et al., 2005).

Remote-sensing is a valuable method for evaluating macrophyte stands and their consequent biophysical and ecological factors. With the advancement in sensor technology and processing techniques, radiometric data can be used to estimate vegetation features (Dierssen et al., 2003), biomass, and even chemical composition (Tilley et al., 2003). Remote-sensing photography is commonly used to create cover maps of aquatic plants either in general or specific population or communities (Abeysinghe et al., 2019). Both emergent and submerged vegetation has been successfully mapped using remote-sensing videography (Samiappan et al., 2017; Rupasinghe & Chow-Fraser, 2021). The present study uses the remote-sensing technique to assess the role of common reed in improving the ecosystem quality of the Idku wetland via its capacity to sequester nutrients in its tissues. This investigation can help restore the eutrophic ecosystem of the Idku wetland. In addition, this study aims to evaluate the forage quality of harvested biomass as a recycling approach.

Materials and Methods

Study site

With an area of approximately 126km^2 (Ali & Khairy, 2016), Lake Idku is the third largest coastal lake in the Northern Deltaic coast with 17.3% open-water and the rest is covered by aquatic plants and islands (Khalil & Rifaat, 2013). The water depths of the lake range from 0.1 to 1.4m with maximum depths of 1 m at the center and eastern portions (El Kafrawy et al., 2018). Lake Idku is a shallow brackish seashore basin in El-Behira Governorate, which is approximately 40km east of Alexandria and 18km west of the Rosetta branch of the Nile River (Galal et al., 2012). The lake is approximately 16-km long and 6-km wide on average. It contains a tiny passage that connects it to the Mediterranean Sea (Boughaz El-Maadia). Lake Idku is one of the most important sources of fish production (Mehanna, 2009). The drainage water of Lake Idku comes from three main drains: Bersik, Idku, and El-Bousily, which all flow into the east coast of the lake (Galal et al., 2012). El-Khairy Drain is also connected to drainage water sources such as the El-Bousely, Idku, and Damanhour subdrains, which deliver massive amounts of drainage water from more than 300 fish farms (Badr & Hussein, 2010). Through Boughaz El-Maadia, 3.3106m^3 of brackish water per day is introduced into Abu Qir Bay from Lake Idku (Shakweer, 2006).

Study species

Phragmites australis (Cav.) Trin. ex Steud (common reed), which belongs to the Poaceae family, is a worldwide angiosperm wetland species with a wide range of habitats that is believed to be one of the most extensively distributed and valuable species in the world. It is well-known in Egypt as the main component of reed stands along lakeshores where it forms enormous beds in shallow water. The *P. australis* green plants are highly appealing to sheep, goats, cattle, and other wildlife (Häkkinen, 2007; Hansmann, 2008; Huhta, 2009; Köbbing et al., 2013). Mollusks, various crustaceans, and aquatic insects feed on the common reed waste (Lambert, 2005; Shaltout & Al-Sodany, 2008). Guda (2018) suggested that *P. australis* could be used as fodder under appropriate conditions. Sun-dried *P. australis* leaves are a high-fiber and high-protein source for rabbits (Kadi et al., 2012). The plants absorb mineral nutrients from water, capture carbon dioxide from air, metabolize them to produce plant biomass, and absorb the carbon in their biomass. Therefore, these plants offer multiple ecological and economic uses.

Selection and mapping of the study stations

Six stations were overlaid on the air photograph map after performing supervised classification using the geographic information system (GIS) [ArcGIS (ver. 10.1)] program to identify the places swamped with a common reed cover in the lake area as much as possible. To assist the field teams in navigating to the sampling stations, the geographic positions were uploaded to Geographic Positioning System units. The investigated stations and their distribution were plotted, as shown in Fig. 1.

Plant sampling and biomass estimation

In each of the six selected stations, six quadrats (0.5 × 0.5m) were chosen at random from two sites. Common reed samples were collected from each quadrat, sealed in plastic bags, and transported to the laboratory for further analysis. The plant samples were gently washed twice using tap water to remove the debris before rinsing them with deionized water. Each sample was divided into three sections (shoot, rhizome, and root). All samples were oven-dried to a consistent weight at 60 – 65°C, and the dry weights were used to quantify the biomass and stand productivity in the lake area using remote-sensing.

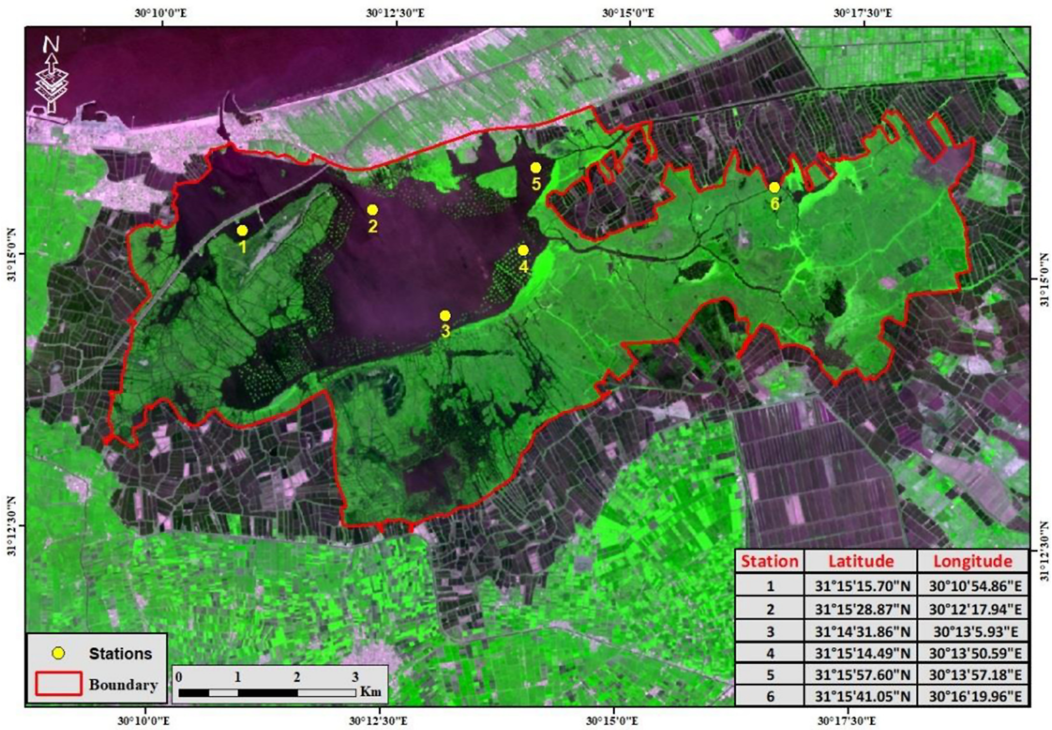

Fig. 1. Lake Idku location map showing the study sites and their coordinates [obtained from the National Authority for Remote-Sensing and Space Sciences (2018)]

Plant analysis

Inorganic elements

Each oven-dry plant part sample was homogenized by grinding it in a metal-free plastic mill and allowing it to pass through a 2-mm mesh sieve. One gram of the ground material was digested in a 20-ml tri-acid mixture of HNO_3:$HClO_4$:HF (1:1:2 V:V:V) until a clear digest was formed, filtered using a Whatman No. 1 filter paper, and diluted into 50 ml with double-deionized water (Lu, 2000). Total nitrogen (N) was determined using the Kjeldahl method. Phosphorus (P) was determined by the molybdenum-blue method using a spectrophotometer (CECIL CE 1021). Calcium (Ca) was determined using the ethylenediaminetetraacetic acid (EDTA) titration method (Trivedy et al.,1987). Potassium (K) was determined using a flame photometer (CORNING M410), and magnesium (Mg) was determined using an atomic absorption photometer (Shimadzu AA-6200). By multiplying the element concentration in the plant part with its standing-crop production from the entire lake, the nutrient standing stock (tons per lake) of the different common reed organs was estimated.

Organic nutrients and nutritive value

To determine the ash percentage, 1 g of each air-dried sample was ignited in a muffle furnace at 550°C for 6h (Allen, 1989). The crude fibers were determined using the Soxhlet extraction method, and the ether extract (EE) was determined by extracting the plant with ether (Allen, 1989). By following the process employed by Adesoganl et al. (2000), the total protein content was calculated by multiplying the N concentration by a factor of 6.25. Carbohydrate [nitrogen-free extract (NFE)] was calculated using Equation (1) (Le Houérou, 1980).

NFE (in % dry matter)= 100 − (TP + CF + crude fat + ash) (1)

where TP represents the total protein and CF denotes the crude fiber. The digestible crude protein (DCP) was estimated using the following equation (Demarquilly & Weiss, 1970):

DCP (in % dry matter)= 0.929 TP (in % dry matter) − 3.52. (2)

The total digestible nutrients (TDNs) were estimated according to the equation used by Naga & El-Shazly (1971).

TDN (in % dry matter) = 0.623 (100 + 1.25 EE) − CP0.72 (3)

where EE and CP are the EE and CP percentages, respectively. The digestible energy (DE) was evaluated using the following equation (NRC, 1984):

DE ($Mcal \cdot kg^{-1}$) = 0.0504 TP (%) + 0.077 EE (%) + 0.02 CF (%) + 0.000377 (NFE)2 (%) + 0.011 (NFE) (%) − 0.152. (4)

The metabolized energy (ME) was calculated as follows (Garrett, 1980):

ME = 0.82 DE (5)

Net energy (NE)= 0.50 ME (Le Houérou, 1980) (6)

Moreover, the gross energy (GE) was calculated using the following equation (NRC, 1984):

GE ($kcal \cdot 100 \cdot g^{-1}$)= 5.72 TP (%) + 9.5 EE (%) + 4.79 CF (%) + 4.03 NFE (%) (7)

Organic carbon and carbon sequestration

The following equations [Equations (8) and (9)] were used to determine the organic carbon (OC) (Armecin & Gabon, 2008):

OM (%)= 100 − ash (%) (8)

OC (%)= OM (%)/1.724 (9)

where 1.724 is the van Bemmelen factor, i.e., organic matter (OM) contains 58% OC.

The carbon sequestration potential (CSP) of the common reed was calculated by multiplying the OC per gram of dry weight by the biomass of that species (Wang et al., 2011a). The overall CSP value in the lake was calculated by multiplying CSP by the coverage area of the species.

Water and sediment sampling and analysis

Three subsurface water-composite samples (1 l each) were collected from each station using a PVC tube column sampler. They were subsequently deposited in plastic bottles, chilled, and transported cold to the laboratory for chemical analysis. The percentages of nitrates and phosphates were determined in the laboratory using a Shimadzu double-beam spectrophotometer (UV-150-02) at the required parameter wavelength according to Strickland & Parsons (1968). According to Allen (1989), calcium and magnesium were determined using meroxide and erichrome black T as indicators in the titration against 0.01N versenate solution (EDTA disodium salt), whereas potassium was determined using a flame photometer (CORNING M410). The permanganate-oxidation method was used to assess the amount of oxidizable OM in water (FAO, 1975).

A sediment sample was taken from each quadrat, which was merged into three composite samples from each station. The sediment samples were collected using a Peterson grab sampler, as described by Boyd & Tucker (1992), stored in cleaned plastic bags, and cooled in an icebox before being transported to the laboratory for analysis. The samples were air-dried, ground, and sieved using a 2-mm sieve. Subsequently, sediment–water extracts of 1:5 (w/v) were prepared for chemical analysis. The samples were air-dried, crushed, and sieved through a 2-mm sieve before being produced as sediment–water extracts at a ratio of 1:5 (w/v) for chemical analysis. Total N was estimated as described by Allen (1989) using the micro Kjeldahl method, whereas Allison & Richards (1954) employed the UNICO 2100 UV spectrophotometer to determine phosphorous (P). The same methods for the water analysis were used to determine calcium, magnesium, and potassium (Allen, 1989). The OC levels were multiplied by 1.72 to calculate OM (Armecin & Gabon, 2008).

Remote-sensing technique

Topo to Raster (DEM) interpolation

The Topo to Raster tool was used to map the three-dimensional spatial distribution of the chemical parameters of water and sediment. This method applies constraints to generate a hydrologically valid digital elevation model (DEM) that incorporates a corresponding drainage structure and accurately portrays the ridges and streams from the input contour data by interpolating the elevation values for a raster.

Coverage area of P. australis per lake using remote-sensing

Data acquisition and processing

This study used the Sentinel-2A satellite image. The image was taken in 2018 with a 10-m spatial resolution. No sensor flaws or clouds appeared in the image. The Landsat image was downloaded in GeoTIFF format from the United States Geological Survey Earth Explorer website (http://earthexplorer.usgs.gov/). The image was projected onto a Universal Transverse Mercator (UTM) coordinate system using the World Geodetic System 1984 datum assigned to UTM Zone 36 using the ArcGIS 10.1 software. The FLAASH Model (Perkins et al., 2005) was used to correct the atmospheric effects to minimize the noise effect. The FLAASH Model could correct collective and multiplicative atmospheric effects (Wu et al., 2014).

Image processing

The images were analyzed using the ENVI 5.1 and ArcGIS 10.1 software for image processing, analysis, and presentation. The research region was clipped for aquatic-vegetation categorization and mapping (i.e., extracted from the image). The most often used indicator for highlighting the vegetative zones in satellite images is the Normalized Difference Vegetation Index (NDVI) (Gandhi et al., 2015). It can obtain important information on the state of vegetation cover and vegetation structure (Yengoh et al., 2015). The NDVI scale ranged from −1 to +1. Equation (10) (Mokarram et al., 2015) was used to determine NDVI.

$$NDVI = (NIR - RED)/(NIR + RED) \quad (10)$$

Supervised classification was performed using prior knowledge on the study area in the field trip. Then, *P. australis* was separated using the extract-by-value tool.

Statistical analysis

After the data were evaluated for normality, a one-way analysis of variance was used to analyze the variation in the plant factors among the studied stations using the SPSS software (SPSS, 2006). When the differences were significant, a post hoc test was performed using the Duncan test.

Results

Water characteristics

Figure 2 shows the values and distribution of water OM and the inorganic nutrients (NO_3^{-1}, PO_4^{-1}, Ca^{+2}, Mg^{+2}, and K^{+}) using GIS in the six stations in Lake Idku. Station 1 (S1, i.e., the western part of the lake) exhibited the highest OM percentage (0.87%) as well as Ca, Mg, and

K (87.5, 10.77, and 154.95mg·l^{-1}, respectively). In addition, S10 (the eastern part) exhibited the highest NO_3^{-1} value (13.63mg·l^{-1}) but the lowest PO_4^{-1} (3.55mg·l^{-1}). The GIS technique indicated that the water in the western part of Lake Idku was rich in OM, Mg, and K, whereas the east and middle northern sections were rich in PO_4^{-1} and Ca, respectively. In addition, the water in the eastern and western parts of the lake were rich in NO_3^{-1}. However, the eastern and southern sections of the lake exhibited low water nutrient and OM contents.

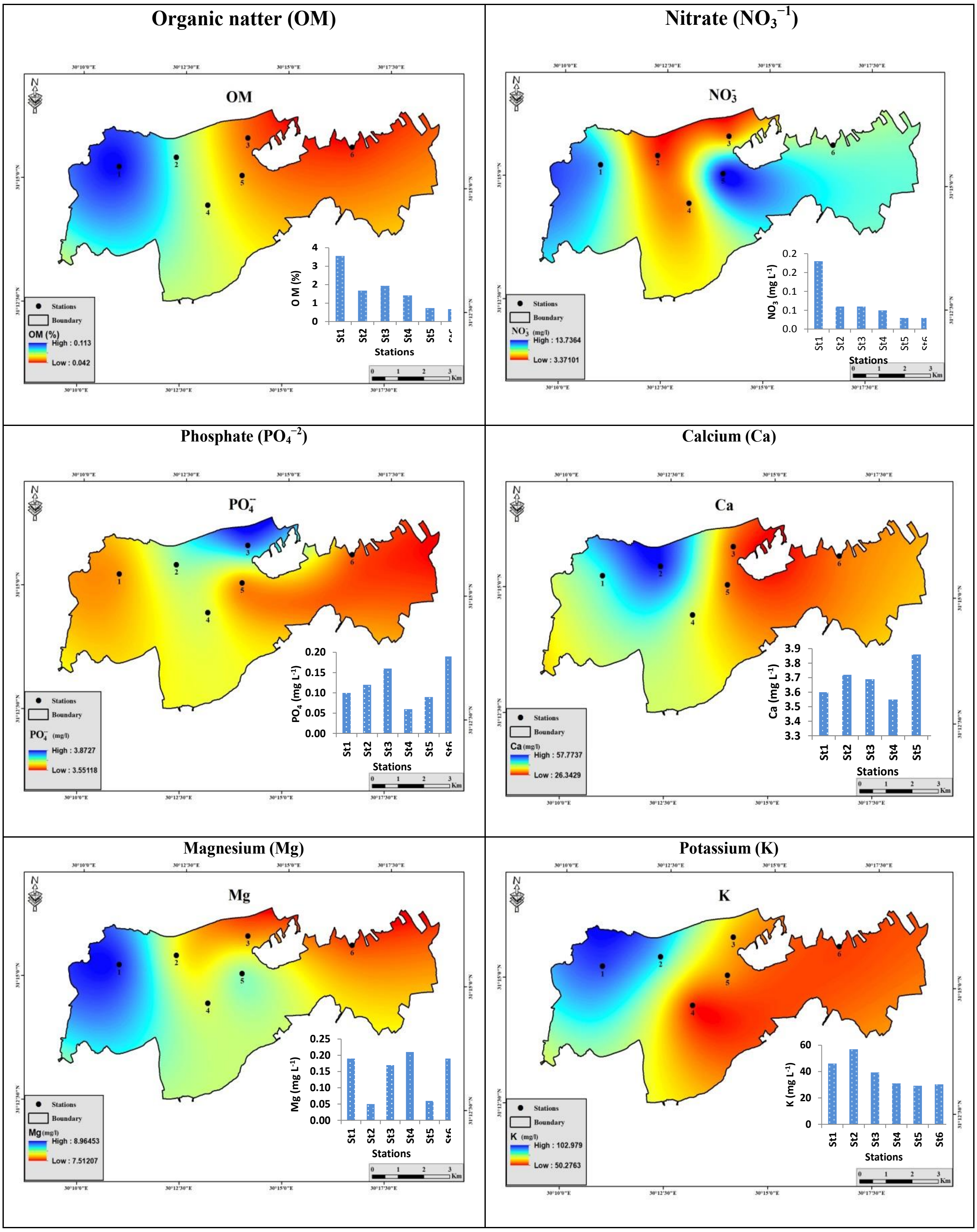

Fig. 2. Spatial distribution of the chemical characteristics of the Lake Idku water samples using the GIS techniques

Sediment characteristics

The results of the physicochemical analysis of the Lake Idku sediments in the six study stations (Fig. 3) showed that S1 exhibited (P< 0.001) the highest K content (605.99mg·kg^{-1}) but the lowest total N (0.31mg·kg^{-1}) and P (0.09 mg·kg^{-1}) contents. In addition, S8 had the highest OM (18.88%), Mg (48.90mg·kg^{-1}), and P (0.43mg·kg^{-1}) contents, whereas S5 had the lowest calcium (177.36mg·kg^{-1}) content. S7 exhibited the lowest OM (5.27%) content. Simultaneously, the S4 sediment contained the highest concentration of Ca (2017.43mg·kg^{-1}), whereas the S12 sediment exhibited the lowest K content (230.13mg·kg^{-1}). The GIS technique indicated that the western section of the lake had the highest contents of OM, N, Ca, and K sediments, whereas the middle section had the highest contents of P sediment. The eastern and western sections of the lake were rich in Mg.

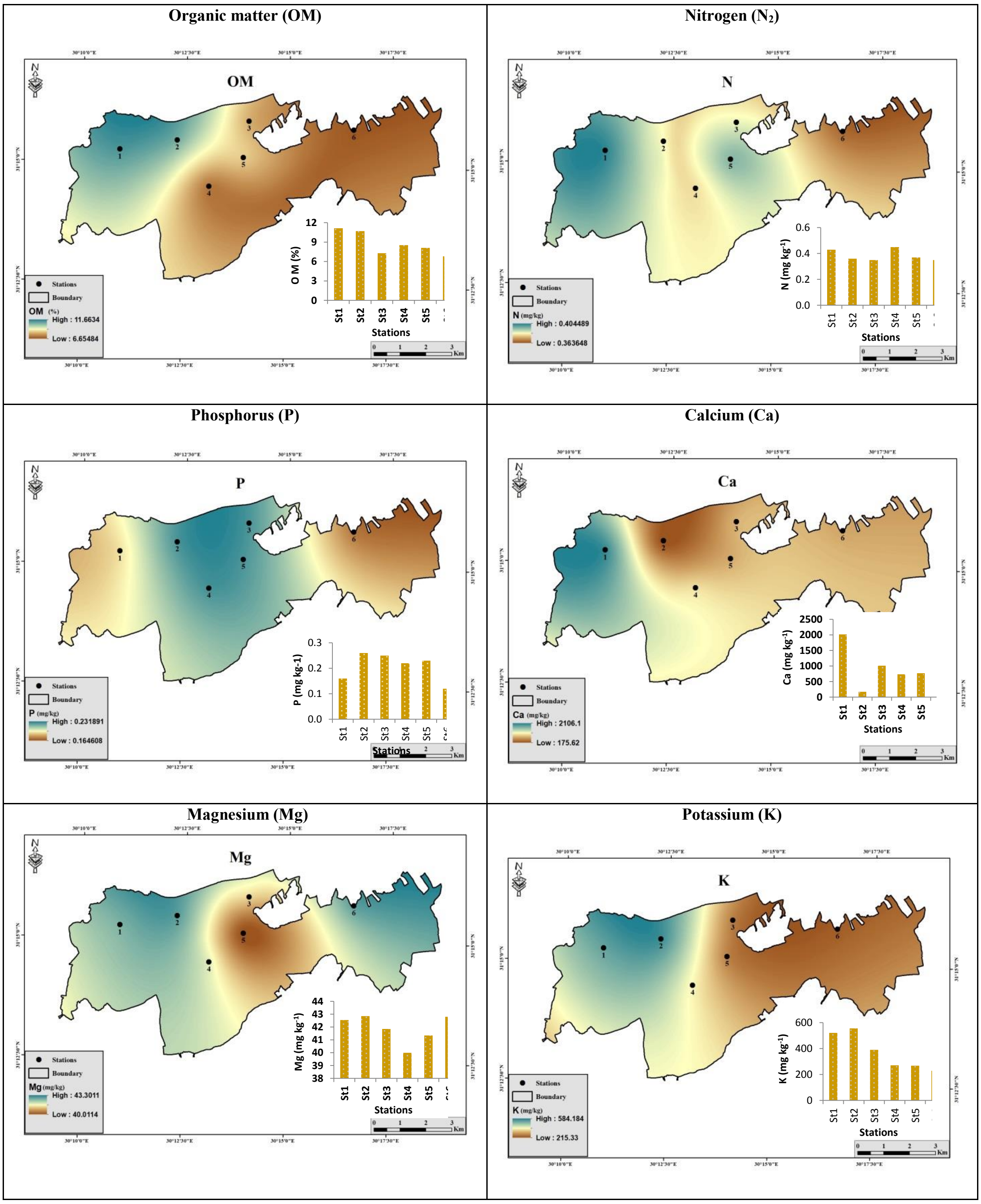

Fig. 3. Spatial distribution of the chemical characteristics of the Lake Idku bottom sediment using the GIS techniques

Coverage area of P. australis

The application of remote-sensing and GIS technique revealed that the common reed approximately covered 14.6% (1840 ha) of the entire lake area (Fig. 4). We need to note that common reed was dense on the lake circumference, where the densest part could be found at the eastern section. Meanwhile, low vegetation existed in the middle open-water section.

Plant biomass and production

The statistical analysis indicated a significant (P< 0.001) difference in *P. australis* biomass among the different sampled stations (Table 1). The plant root, rhizome, and shoots recorded their highest biomass (533.4 ± 44.8, 1394.2 ± 38.4, and 6192 ± 379.2g·m^{-2}, respectively) in S6 in the eastern section of the lake. However, the lowest biomass of the root and rhizome (66.2 ± 6.6 and 221.6 ± 20.4g·m^{-2}) and that of the shoot (1777.8 ± 101.6) were recorded in S4 and S3, respectively, in the middle open-water section. The biomass was distributed (in grams per square meter) as follows: shoot (3161.6) > rhizome (849.8) > root (299.0).

The standing-crop production of the common reed was obtained by multiplying the dry biomass of the plant part (tons per hectare) by the plant coverage area in the entire lake. The results showed that Lake Idku could produce 116377, 31281, and 11006 tons of dry biomass from the shoots, rhizomes, and roots, respectively (Fig. 5). According to the obtained data, the standing dry biomass of the common reed shoots was 2.75 times that of the underground parts (roots and rhizomes) (Fig. 5). The sequence in which the biomass production was distributed in the plant parts was as follows: shoots > rhizomes > roots.

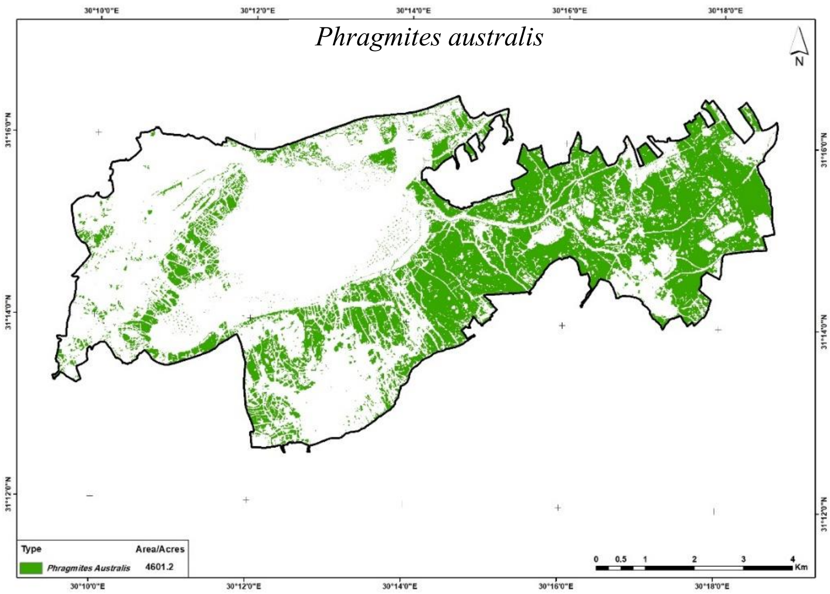

Fig. 4. Coverage area of *P. australis* in Lake Idku

TABLE 1. Dry biomass of the different parts of common reed in the sampled stations (means ± standard deviation). The maximum and minimum values are underlined

Stations	Dry biomass (g m^{-2})		
	Root	Rhizome	Shoot
Station 1	157.0 ± 12.2d	1101.4 ± 60.8b	3439.4 ± 224.0b
Station 2	448.4 ± 40.4ab	496.4 ± 42.0c	2498.4 ± 180.8c
Station 3	66.2 ± 6.6e	221.6 ± 20.4d	2014.6 ± 169.2c
Station 4	206.6 ± 18.4c	569.6 ± 49.2c	1777.8 ± 101.6d
Station 5	382.4 ± 32.2b	1315.4 ± 67.8a	3047.6 ± 229.6b
Station 6	533.4 ± 44.8a	1394.2 ± 38.4a	6192 ± 379.2a
F-value	1365.8***	2795.6***	10650.8***
Average (g m^{-2})	**299.0 ± 182.**8	**849.8 ± 484.7**	**3161.6 ± 1609.**0

*** Significance at P< 0.001. Means in the same column that have the same letter(s) are not significant (Duncan's test).

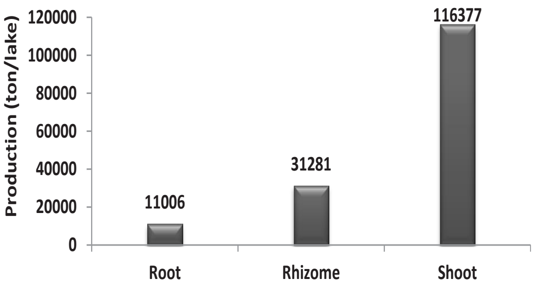

Fig. 5. Standing-crop production of the different parts of the common reed in the entire coverage area of Lake Idku

Inorganic nutrients

A significant variation in all investigated nutrient elements (except P) in the different tissues of *P. australis* was observed in the different stations (Table 2). Most of the investigated nutrients (except Mg) in higher concentrations accumulated in the tissues above the ground than in the parts below the ground. Approximately equal distributions of P were observed in the three parts of *P. australis* in which its concentration ranged between 0.2% and 0.4% in the plants in S1 and S6, respectively. We found that the highest Ca and K concentrations (5067.1 ± 245.6 and 9604.4 ± 362.8mg·kg^{-1}) were recorded in the shoots in the S1 and S4 plants, respectively, whereas the lowest concentrations (590.3 ± 46.8 and 3301.5 ± 242.8mg·kg^{-1}) were recorded in the rhizomes in S2 and roots in S1. Further, the highest N and lowest Mg contents (2.63± 0.18 and 424.5 ± 16.5mg·kg^{-1}) were recorded in the rhizomes in S1 and S5, respectively, whereas the highest Mg and lowest N contents (720.8 ± 22.6 and 0.52 ± 0.04 mg·kg^{-1}) were recorded in the roots of S2 and S6, respectively. The order of nutrient elements in the different tissues of the common reed was as follows: K > Ca > Mg > N > P.

TABLE 2. Mineral-nutrient contents of the different parts of common reed in different stations in Lake Idku (mean ± standard deviation) [The maximum and minimum values are underlined]

Stations		Mineral nutrients of *Phragmites australis*				
		%		mg kg^{-1}		
		P	N	Ca	K	Mg
Root	St 1	0.2 ± 0.01	1.68 ± 0.13 a	2607.3 ± 345.5 d	3301.5 ± 242.8 d	448.8 ± 26.7 d
	St 2	0.3 ± 0.01	1.36 ± 0.11 b	4525.9 ± 462.8 a	7465.9 ± 453.2 b	720.8 ± 22.6 a
	St 3	0.3 ± 0.01	0.78 ± 0.05 d	3935.6 ± 285.4 b	6865.6 ± 326.5 c	659.5 ± 28.6 b
	St 4	0.3 ± 0.01	1.12 ± 0.07 cd	3197.7 ± 196.8 c	6790.6 ± 285.4 c	627.5 ± 30.4 b
	St 5	0.3 ± 0.01	1.00 ± 0.09 c	2754.9 ± 205.2 d	6452.9 ± 356.4 c	558.5 ± 32.7 c
	St 6	0.4 ± 0.01	0.52 ± 0.04e	3197.7 ± 267.5 c	9041.6 ± 487.6 a	520.5 ± 25.8 c
Average ± SD		**0.3 ± 0.1**	**1.08 ± 0.41**	**3369.8 ± 731.5**	**6653.0 ± 1881.6**	**589.3 ± 99.1**
F-value		**0.85**	**12.82****	**1236.8****	**11562.3****	**1462.2****
Rhizome	St 1	0.2 ± 0.01	2.63 ± 0.18 a	934.7 ± 67.5 c	5440.0 ± 367.5 d	476.3 ± 18.9 b
	St 2	0.3 ± 0.01	2.45 ± 0.13 a	590.3 ± 46.8 d	6415.4 ± 285.4 c	676.5 ± 26.8 a
	St 3	0.3 ± 0.01	1.02 ± 0.07 c	1229.9 ± 102.3 b	7616.0 ± 475.6 b	654.3 ± 32.2 a
	St 4	0.3 ± 0.01	1.43 ± 0.12 b	1426.7 ± 124.3 a	8891.6 ± 455.2 a	635.5 ± 28.6 a
	St 5	0.2 ± 0.01	1.36 ± 0.08 b	1525.0 ± 135.8 a	7465.9 ± 336.8 b	424.5 ± 16.5 c
	St 6	0.4 ± 0.0	0.78 ± 0.06 d	1180.7b ± 94.6 c	5890.2 ± 252.5 c	517.8 ± 20.7 b
Average ± SD		**0.3 ± 0.1**	1.58 ± 0.78	**1147.9 ± 341.8**	**6953.2 ± 1278.2**	**564.2 ± 105.1**
F-value		**0.82**	**15.84*****	**2560.2****	**1087.6****	**985.4****
Shoot	St 1	0.2 ± 0.01	2.58 ± 0.22 a	5067.1 ± 245.6 a	6227.8 ± 244.6 d	594.5b ± 28.4 c
	St 2	0.2 ± 0.01	2.24 ± 0.18 b	1229.9 ± 82.8 e	2401.1 ± 178.4 f	695.5 ± 44.8 a
	St 3	0.3 ± 0.01	1.13 ± 0.08 d	2607.3 ± 203.6 c	5628.3 ± 3.41.7 e	612.8 ± 36.7 b
	St 4	0.3 ± 0.01	1.64 ± 0.13 c	737.9 ± 68.5 f	9604.4 ± 362.8 a	620.5 ± 29.4 b
	St 5	0.2 ± 0.01	1.33 ± 0.11 c	3050.1 ± 220.4 b	8216.2 ± 425.9 b	557.2 ± 22.5 c
	St 6	0.3 ± 0.1	0.88 ± 0.06 d	1623.4 ± 124.8 d	7540.9 ± 288.4 c	569.5 ± 17.8 c
Average ± SD		**0.3 ± 0.1**	1.63 ± 0.66	**2386.0 ± 1569.2**	**6603.1 ± 2499.5**	**608.3 ± 49.2**
F-value		**0.64**	**20.46*****	**3482.8****	**15673.5*****	**1874.3****

** and *** significant at P< 0. 01 and P< 0.001, respectively. Means in the same column with the same letter(s) are not significant (Duncan's test).

The nutrient standing stock that could be accumulated in the different tissues of the common reed in the entire lake indicated that the plant shoots could remove the highest contents of all mineral nutrients than the rhizomes and roots (Table 3). Generally, the common reed can remove 4.76, 16.69, 261.59, 1168, and 903.46tons per lake of P, N, Ca, K, and Mg, respectively.

Organic nutrients and nutritive value

The organic-nutrient analysis of the common reed shoots (Table 4) indicated that the NFE content represented the main component with a value 43.0% ± 11.5%, followed by CF (31.1% ± 8.9%), TP (10.2% ± 2.0%), and EE (8.3% ± 1.7%). In contrast, the ash content exhibited the lowest value (7.4% ± 0.8%). By using the remote-sensing technique, the common reed in the entire lake was found to convert the absorbed carbon dioxide and mineral nutrients to dry biomass consisting of 4.83, 18.3, 4.31, 5.82, and 25.02 tons of fats, crude fibers, ash, total proteins, and carbohydrates, respectively (Fig. 6).

The nutritional value of the common reed shoots indicated that the DCP value was 5.9%, whereas the TDN value was 61.4% (Table 4). In addition, the other determined nutritive values of DE, ME, NE, and GE were 2.8, 2.3, 1.2, and 459.6 Mcal·kg^{-1}, respectively.

CSP

CSP of the common reed demonstrated significant variation among the six studied stations in Lake Idku (Table 5). The highest CSP value of the roots (200.26 ± 16.52g·m^{-2}) was recorded in S2, whereas the lowest value (29.20 ± 22.40 g·m^{-2}) was recorded in S3 with an average value of 117.35 ± 68.97g·m^{-2}. On the other hand, the highest CSP value of the rhizomes (768.27 ± 42.55g·m^{-2}) was recorded in S5, whereas the lowest value (80.98 ± 5.74g·m^{-2}) was recorded in S3 with an average value of 455.45 ± 275.26g·m^{-2}. Moreover, the plant shoots achieved the highest CSP value (3124.73 ± 198.2g·m^{-2}) in S4 and the lowest value (948.72± 7.25g·m^{-2}) with an average value of 1638.40 ± 794.75g·m^{-2}.

TABLE 3. Mineral-nutrient quantities removed by the common reed production in entire Lake Idku

	Mineral nutrients (t/lake)				
	P	**N**	**Ca**	**K**	**Mg**
Root	0.33	1.21	37.09	73.19	64.94
Rhizome	0.94	5.00	35.97	217.40	175.17
Shoot	3.49	10.47	188.53	877.48	663.35
Total	**4.76**	**16.69**	**261.59**	**1168.08**	**903.46**

TABLE 4. Organic nutrients and nutritional values of *P. australis* shoot parts in Lake Idku

Variable		**Content**
Organic contents		
EE	%	8.3 ± 1.7a
CF	%	31.1 ± 8.9ab
Ash	%	7.4 ± 0.8b
TP	%	10.2 ± 2bc
NFE	%	43 ± 11.5ab
Nutritional value		
DCP	%	5.9 ± 0.5de
TDN	%	61.4 ± 14.2a
DE	Mcal kg^{-1}	2.8 ± 0.8a
ME	Mcal kg^{-1}	2.3 ± 0.7a
NE	Mcal kg^{-1}	1.2 ± 0.4a
GE	Mcal kg^{-1}	459.7 ± 98.0a

EE (ether extract), CF (crude fiber), TP (total protein), NFE (nitrogen-free extract). DCP (digestible crude proteins), TDN (total digestible nutrients), DE (digestible energy), ME (metabolized energy), NE (net energy), GE (gross energy.

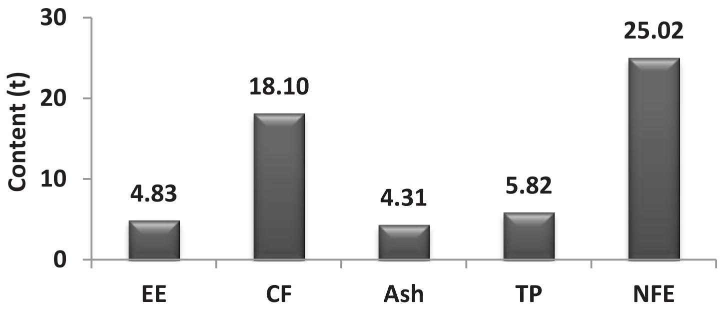

Fig. 6. Total productivity of the organic nutrients (tons per lake) of *P. australis* in Lake Idku [EE (ether extract), CF (crude fiber), TP (total protein), NFE (nitrogen-free extract)]

TABLE 5. CSP of the different parts of *P. australis* (grams per square meter). The maximum and minimum values are underlined.

Stations	Carbon sequestration potential (CSP) g m^{-2}		
	Roots	Rhizomes	Shoot
Station 1	69.18 ± 6.21e	606.87 ± 22.4c	1795.49 ± 98.5b
Station 2	<u>200.26 ± 16.52a</u>	270.70 ± 18.65e	1318.79 ± 86.2c
Station 3	<u>29.20 ± 22.40f</u>	<u>80.98 ± 5.74f</u>	1051.7 ± 101.00e
Station 4	77.90 ± 5.86d	303.98 ± 21.58e	<u>948.72 ± 7.25f</u>
Station 5	185.61 ± 14.72b	<u>768.27 ± 42.55a</u>	<u>3124.73 ± 198.2a</u>
Station 6	141.97 ± 10.63c	701.92 ± 38.62b	1590.96 ± 114.26d
Average	117.35 ± 68.97	455.45 ± 275.26	1638.40 ± 794.75
F-value	1345.26***	2690.45***	5875.83***

***P< 0.001. The means in the same column with the same letter(s) are not significant (Duncan's test).

By employing the remote-sensing technique, the common reed demonstrated the potential to sequester 3.015 t of carbon, whereas the rhizomes and roots demonstrated the potential to store 0.838 and 0.216 t of carbon, respectively, from the entire lake (Fig. 7). CSP of the common reed shoots was clearly indicated to be 2.9 times more than the sum of the CSP values of the roots and rhizomes.

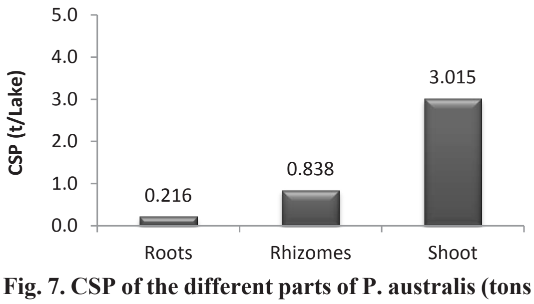

Fig. 7. CSP of the different parts of P. australis (tons per Lake Idku area)

Discussion

Despite their importance, nitrogenous compounds such as nitrate, are among the unique components of water where their fertility is considered the most important sources of ammonia nitrogen for algae and aquatic plants (Farouk, 2018). The average concentration of nitrates in the Lake Idku water was 36.76 times more than that in the Manzala lake, as recorded by Abu Khatita et al. (2017). The results of the current study on the inorganic nitrogen compounds indicated that the highest values were recorded nearest the mouth of the drains because of the increase in the accumulation of organic compounds, which agreed with the results by Saeed (2013), El Kafrawy et al. (2015), and Farouk (2018). In the same context, the average value of phosphate (3.6mg/L) was more than (0.39mg/L) that recorded by Shetaia et al. (2020) in Lake Idku and more than (0.210mg/L) that in the Manzala lagoon water (Abu Khatita et al., 2017). In addition, the value obtained by the present study was 1.5–36 times higher than the recommended optimum range of phosphate (0.01–0.20mg/L) for maximum growth and production of most aquatic lives (Ferreira et al., 2011). Our results indicated that Lake Idku is under critical eutrophication conditions such as Burullus Lagoon (Abd El Fatah et al., 2022). The highest concentrations of

Ca, Mg, and K were 5.83, 2.63, and 67.37 times higher, respectively, than those in the Nile River water.

The results in the present study showed that the sediment OM content was higher than that obtained by Farouk et al. (2020) in Lake Idku. This variation may have been due to the continuous removal of the OM-rich sediments from the lake or variation in the sampling stations. Because of the organometallic complex formation, the increasing OM contents in the sediments could raise the level of metals in the sediments (Shreadah et al., 2008). On the other hand, the accumulation of high OM contents indicated low activity of microorganisms in the decomposition. In the present study, the average sediment N and P contents were lower than those recorded by Ali & Moghanm (2013) and El-Amier et al. (2017) in the Lake Idku sediments. On the other hand, the average K content recorded by Ali & Moghanm (2013) was slightly higher than that in the present study.

Imaging satellite data provide a promising tool for monitoring the common reed because they allow scientists to map the differences in the structure and biomass among plant species (Bourgeau-Chavez et al., 2009; Luo et al., 2017). In the present study, the common reed covered a wide area (1840.5ha), which accounted for 14.6% of the Lake Idku area. Abd El-Hamid et al. (2020) observed that the vegetative coverage areas of Lake Idku increased from 2000 to 2011 and then decreased from 2011 to 2018. For the same plant species, Bourgeau-Chavez et al. (2013) used remote sensing data to record the coverage area of the Great Lakes. They observed that the coverage area of the mapped common reed in Huron Lake (10395ha) was the largest, whereas small areas were observed on the shores of Ontario Lake (13ha). Therefore, remote-sensing technique is a good tool for monitoring the coverage area of aquatic plants.

Estimating biomass is useful in aquatic-plant research, such as studying the species distribution and abundance, succession, and weed-management operations. (Pine et al., 1989; Shaltout et al., 2014). The data obtained in the present study indicated that most metabolic products were stored in the aerial parts of the common reed. The dry biomass of the aerial shoots was approximately threefold higher than that below the ground. In the present study, the shoot dry biomass yield of the common reed averaged 3.16kg·m^{-2}, which is a higher figure (1.99kg·m^{-2}) than that recorded by Shuai et al. (2016). According to Shuai et al. (2016), soil pH, nitrogen availability, and wetland location significantly affected the biomass productivity. In general, common reed is a high-yielding grass whose above-ground net primary production ranges from 3 to 30 tons per hectare. (Allirand & Gosse, 1995; Köbbing et al., 2013). In the current study, the above-ground net primary production (shoot biomass) was 31.62t·ha^{-1} with gross production of 116377.23 tons per lake.

From the results of the current study, we can conclude that the water and sediment of Lake Idku are of low quality because of their high OM and mineral-nutrient contents. Consequently, they require improvement by removing the high mineral contents using aquatic macrophytes. The mineral-nutrient intake of plants varies according to the species and is dependent on the nutrient demands of each species to meet their physiological and biochemical needs (Eid et al., 2012; Abdallah et al., 2020). Macronutrients N, P, and K are the most common limiting factors for plant development in aquatic habitats. The aquatic-plant nutrient concentrations increase as the environmental levels increase, a relationship that is largely dependent on both the species and elements (Bonanno & Giudice, 2010; Ruiz & Velasco, 2010; Eid et al., 2012). The potassium concentration in the plant parts above the ground was higher than that in the tissues below the ground, which was consistent with the findings of Ruiz & Velasco (2010), Eid et al. (2012), and Eid et al. (2020) for the common reed and those of Galal et al. (2021) for *Ludwigia stolinefera*. The P concentration recorded in the different tissues of the common reed was lower than that recorded by Galal et al. (2021) for *L. stolinefera*.

Moreover, the higher contents of calcium and magnesium shoots than those in the rhizomes agreed with the study results of Al-Sodany et al. (2013) on the same species in Burullus Lake. The results of the current study indicated that the common reed demonstrated a high ability to remove 4.76, 16.69, 261.59,1168, and 903.46tons of P, N, Ca, K, and Mg, respectively, owing to its large coverage area and dry biomass production. Therefore, common reed is one of the important aquatic plants that can be employed to improve water and sediment quality through the accumulation and translocation of inorganic nutrients in its tissues.

The main biomass of the common reed is concentrated in the shoots, which store large quantities of inorganic and organic nutrients. The fodder value of the consumed plants is a result of its nutritive value (digestibility and chemical composition). This value is highly influenced by the maturity stage of the plant, soil type, and climatic condition (Le Houérou, 1980; Heneidy & Halmy, 2009). In the current study, the forage value of common reed was estimated based on its chemical constituents because it is high-quality forage for domestic animals such as sheep, goats, and cattle. The order of organic nutrients was indicated as follows: carbohydrates > crude fibers > TP > EE > ash. The same order was reported by Al-Sodany et al. (2013). The forage quality could be expressed in several parameters, such as TDN, DCP, and caloric value (Duiven-Booden & Uivenbooden, 1985). After the digestion loss is deducted, TDN can suitably assess the meal energy available for animals (Lofgreen, 1951). In the current study, the average TDN value (61.4%) of the common reed was slightly lower than that (64.03%) of some grazed wild plants such as *Panicum turgidum* (Heneidy and Halmy (2009) and cultivated common fodder crops such as barley (64 %) and corn (68%) but was higher than that of clover (56%) obtained by Soliman & El Shazly (1978). However, it almost satisfied the nutritional needs of breeding cattle (50.0%) (NRC, 1984) and sheep (61.7%) (NRC, 1975).

According to the Ministry of Agriculture, Fisheries, and Food in England (1975), the minimum protein content of an animal diet varies between 6% and 12% depending on the species. The protein level of the common reed satisfies the needs for animal diets according to the current study. Low protein level efficiency is related to a comparatively low voluntary feed consumption with a protein-deficient diet.

According to Boudet & Rivière (1968) the forage quality indicated that the green parts of the common reed are ranked as exceo allent fodder quality, where its NE and DCP were 5.02MJ kg^{-1} and 5.9%, respectively. Green parts' organic components and nutritional values are commonly within the ranges in feeds frequently used in sheep, goat, and cattle ratios (NRC, 1975, 1978, 1981, 1984). The present and previous studies indicated that the common reed in Lake Idku is not only an excellent substitute fodder but also as fertilizers (Nafea, 2017) for its high productivity, suitable mineral content, organic nutrients, and high nutritional value, as reported for many fodder wild and common fodder crops.

Coastal ecosystems have a high CSP, and there is growing interest in examining their potential in existing and upcoming climate change frameworks (Duarte et al., 2005; Bouillon et al., 2008; Eid & Shaltout, 2016). The common reed had high CSP (819.2g m^{-2}), which were higher than (740.5g m^{-2}) reported by Khan (2013) for the same species. The carbon content (52.2%) was higher compared with 44.7 and 44.0% of the common reed and *Typha orientalis*, respectively (Wang et al., 2011b); 45% of the common reed (Baldantoni et al., 2004); 47.5% of *Echinocloa crusgalli* (Khan, 2013), but lower than 53.6% that reported for *Typha latifolia* (Khan, 2013). It is worth noting that the common reed had the potential to sequester 3.015 t carbon, while the rhizomes and roots had the potential to store 0.216 and 0.838 t carbon from the whole lake.

Conclusions

The sediment and water analysis of Lake Idku indicated that they had high contents of N and P, and thus the lake was under critical conditions of eutrophication. The common reed had a high coverage area (1840.5ha), which amounted 14.6% of the total lake area. The above-ground net primary production (shoot biomass) was 31.62t ha^{-1} with gross production of 116377.23ton per lake. The plant tissues could sequester large quantities of nutrient elements and thus had the potential to treat eutrophication. The common reed shoots had considerable contents of crude protein, lipids, and carbohydrates and high content of Ca and K. Thus, this species could be suggested as a potentially promising supplementary feeding. The current results indicate that the common reed shoots can be used as an excellent fodder. It is one of the important aquatic plants to improve water and sediment quality through the accumulation and translocation of inorganic nutrients in its tissues. The remote sensing data was a successful technique used in mapping the distribution and the coverage area of the common reed in this study, enabling the production calculation. The common reed had the potential to sequester 3.015t carbon, while the rhizomes and roots had the potential to store 0.216 and 0.838 t carbon from the whole lake

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استخدام تقنية الاستشعار من بعد لتقييم دور نبات البوص في استعادة الأراضي الرطبة لبحيرة إدكو في مصر من التخثث

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تعتبر أراضي إدكو الرطبة إحدى بحيرات شمال الدلتا في مصر، وهي مهددة بالتخثث نتيجة للمغذيات التي يتم تصريفها من المناطق المجاورة. ويمكن للنباتات المائية تخزين كميات كبيرة من هذه العناصر الغذائية. لذلك، تهدف الدراسة الحالية إلى تقييم دور نبات البوص في استعادة أراضي إدكو الرطبة المتخثثة. تحتوي مياه البحيرة والرواسب على محتويات عالية من النيتروجين والفوسفور والكالسيوم والبوتاسيوم، مما يزيد من مخاطر التخثث. أوضح استخدام تقنية نظم المعلومات الجغرافية أن مياه البحيرة ورواسبها تظهر تركيزات عالية من العناصر الغذائية غير العضوية في المناطق الأقرب لمصبات الصرف. كما أوضحت تقنية الاستشعار من بعد أن نبات البوص يغطي 1840.5 هكتار (14.6٪ من إجمالي مساحة البحيرة). أنتج المجموع الخضرى للنبات 31.62 طن/هكتار من الكتلة الحية الجافة بصافي إنتاج 116377.23 طن لكل البحيرة. أستطاع نبات البوص تخزين 4.76 و16.69 و261.59 و1168.08 و903.46 طنًا من الفوسفور، النيتروجين، الكالسيوم، البوتاسيوم والماغنسيوم ، على التوالي. بالإضافة إلى ذلك، احتوي المجموع الخضرى على 10.2٪ بروتين خام، و8.3٪ دهون، و43.0٪ كربوهيدرات، وأنتج 459.7 ميجاكلورى/كجم من إجمالي الطاقة. أوضحت النتائج أنه يمكن استخدام المجموع الخضرى لنبات البوص كعلف ممتاز للحيوان. كما استطاع المجموع الخضرى لنبات البوص أن يخزن 3.015 طنًا من الكربون، بينما خزن الريزومات والجذور 0.838 و0.216 طنًا من الكربون على مستوى البحيرة. خلصت هذه الدراسة إلى أن تقنية الاستشعار من بعد هي أداة جيدة لتقدير مساحة التغطية لنبات البوص الذى يمتلك إمكانات عالية لمعالجة التخثث عن طريق تحسين جودة المياه والرواسب من خلال تراكم العناصر الغذائية غير العضوية في أنسجته وإعادة استخدامها كعلف حيوانى ممتاز. بالإضافة إلى ذلك، تساعد هذه النباتات في الحد من ظاهرة الاحتباس الحراري بسبب قدرتها العالية على تخزين كميات كبيرة من الكربون.