Trophic status, phytoplankton diversity, and water quality at Kafr El-Shinawy drinking-water treatment plant, Damietta

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ABSTRACT

This work aims to study the seasonal fluctuation in physicochemical characteristics, trophic status, and some pollutants influencing phytoplankton diversity, and water quality at a compact Kafr El-Shinawy drinking-water treatment plant, Damietta – Egypt seasonally during 2018. Phytoplankton distribution was affected by the trophic status of water, level of pollutants, and physicochemical treatment processes of water. The predominance of phytoplankton species, especially *Aphanizomenon flos aquae* (Cyanophyta), *Gomphosphaeria lacustris* (Cyanophyta), *Microcystis aeruginosa* (Cyanophyta), *Nostoc punctiforme* (Cyanophyta), *Oscillatoria limnetica* (Cyanophyta), *Pediastrum simplex* (Chlorophyta), and *Melosira granulata* (Bacillariophyta) in treated water was much less than that in raw water. Trihalomethanes (THMs) levels in treated waters were higher than in raw water, while lower concentrations of heavy metals were recorded in treated water. Intracellular levels of microcystins were lower, whereas the extracellular levels were higher in treated water than raw water, and the former recorded the highest level in raw water during summer. Hence, the levels of dissolved microcystins and THMs in treated water were higher especially during summer, the season of luxurious growth of *Microcystis* species. Trophic state index (TSI) was relatively high in raw water compared with treated water due to high concentrations of nutrients (total-P, total-N, nitrite, nitrate, and ammonia) in raw water.

Key words | drinking water, microcystins, physicochemical analyses, phytoplankton, trophic state, water quality

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HIGHLIGHTS

- Phytoplankton composition was affected by the trophic status level of water and physicochemical treatment processes of water.
- Phytoplankton cells control the levels of heavy metals in water.
- THMs in treated water increased greater than those in raw water by the effect of physicochemical treatment of water.
- Cyanobacteria produced cyanotoxins in water.

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INTRODUCTION

Water pollution has become one of the most important environmental problems worldwide. Pollutants can be released into the environment as liquids, gases, and dissolved substances which can enter aquatic ecosystems and decrease water quality. The assessment of water quality essentially requires information about the physicochemical and biological properties of water. Temperature, acidity, hardness, pH, sulfate, chloride, dissolved oxygen (DO), biological oxygen demand, and alkalinity are physicochemical properties used for determining water quality (Swarnakar & Choubey 2016). Also, water quality can be assessed through natural bio-indicators; phytoplankton due to their sensitivity to nutrient availability and environmental conditions (e.g. water temperature and level of salinity; Manickam *et al.* 2012). Cyanobacterial growth adversely affects odor, taste, and color of water as some of these cyanobacteria produce potent toxins called cyanotoxins. There are various variants of cyanotoxins that are commonly produced by the genera, *Microcystis*, *Anabaena*, *Aphanizomenon*, *Fischerella*, *Planktothrix*, *Anabaenopsis*, *Aphanocapsa*, *Cylindrospermopsis*, *Gleotrichia*, *Gomphosphaeria*, *Hapalosiphon*, *Nodularia*, *Nostoc*, *Oscillatoria*, *Phormidium*, *Pseudanabaena*, and *Synechococcus* (Vesterkvist *et al.* 2012; Paerl & Otten 2013). Although cyanobacterial cells can survive in water for long periods due to their ability to form thick-walled resting cells, the production of cyanotoxins is affected by several environmental conditions such as temperature, salinity, irradiance, and nutrients (Zhang *et al.* 2020).

One of the most serious water quality problems is eutrophication, which means the enrichment of water by organic and inorganic nutrients. Eutrophication causes structural changes to water and favors developing algae and plants. Oligotrophic, mesotrophic, eutrophic, and hypertrophic have been used by biologists to describe the various nutritional statuses of water. Oligotrophic means low nutrient concentrations and low algal growth, while hypertrophic state means high nutrients and high algal growth. Generally, nutrient concentration (nitrogen and phosphorus) and algal chlorophyll were used to assess water eutrophication. Trophic state index (TSI) is considered as one of the assessment methodologies of water eutrophication. Ray *et al.* (2020) found that water pollution and eutrophication control the biodiversity of phytoplankton species and have a direct and indirect effect on biochemical constituents of phytoplankton cells.

The availability of good quality water is an indispensable feature for preventing diseases and improving the quality of human life. Water treatment plants mainly aim to improve the quality of water to make it appropriate for drinking and human consumption. Water treatment involves some physical processes such as settling and filtration, chemical processes such as disinfection and coagulation, in addition to biological processes such as slow sand filtration. As a result of chlorine disinfection during treatment of drinking water, trihalomethanes (THMs) including chloroform, dichlorobromomethane, and dibromochloromethane are produced as byproducts. THMs have short-term and long-term hazardous effects on human health.

Kafr El-Shinawy drinking-water treatment plant is a compact unit that is designed to produce safe drinking water for a small community that has no access to a central water treatment facility. The treatment processes at this water treatment plant include coagulation, flocculation, sedimentation, and filtration. In developing countries, the water quality patterns differ amongst drinking-water plants, and no previous studies have been conducted on water quality and phytoplankton composition at Kafr El-Shinawy drinking-water treatment plant. Therefore, the present work aims to shed light on the water quality at Kafr El-Shinawy treatment plant as it is the main source of drinking water of Kafr El-Shinawy village. In this study, the effect of seasonal changes in physicochemical characteristics, trophic status of water as well as levels of pollutants, and microbial toxins on water quality and phytoplankton diversity at Kafr El-Shinawy drinking-water treatment plant will be determined and discussed.

MATERIALS AND METHODS

Sampling sites

The study site was a compact Kafr El-Shinawy drinking-water treatment plant that is situated at 31°41.816′N and

31°17.325′E. Water samples were collected seasonally (at 3-month intervals) from January to December 2018 in glass bottles from both the intake (the first unit) and output (the last unit) sites of Kafr El-Shinawy water treatment plant to determine the phytoplankton composition in relation to physicochemical properties, trophic status, and levels of pollutants of the native and treated water.

Physicochemical properties of water

Temperature, turbidity, pH, and electrical conductivity (EC) were measured in the field. The temperature and pH of water samples were measured using the laboratory glass thermometer and a pH meter (model HI 8314; Hanna Instruments Ltd), respectively. Water turbidity was measured directly using the Hanna instrument microprocessor turbidity meter. Water EC was measured using Jenway conductivity meter model 470. Total alkalinity, DO, biochemical oxygen demand (BOD), silica, ammonia, nitrite, nitrate, total nitrogen, and ortho-phosphate were estimated in the laboratory according to APHA (1996). The total phosphorus (TP) in water samples was determined according to Grasshoff (1975).

The heavy metals, iron, manganese, zinc, copper, chromium, cobalt, cadmium, nickel, and lead in water samples were assayed in water by using a Perkin-Elmer 2380 atomic absorption spectrophotometer as described by Sudharsan *et al.* (2012). All physicochemical analyses of water samples were triplicated.

Trihalomethane compounds in native and treated water were estimated according to U.S. EPA Method 551.1 (1995).

Phytoplankton composition

Raw and treated water samples were collected seasonally for microscopic examination using a conical bolting nylon net of 0.069 mm mesh and a mouth diameter of 35 cm with the help of an outrigger canoe. The samples were filtered through fine mesh nylon and fixed in Lugol's solution and 4% formalin and algal cells were enumerated using an inverted light microscope. Phytoplankton identification was performed with reference to Tikkanen (1986) and Botes (2003) using an EXACTA + OPTECH GmbH light microscope (Model B3) – Code K7161, Germany.

Extraction and estimation of intracellular and extracellular microcystins

To determine the intracellular (particulate) and extracellular microcystins in raw and treated water, subsamples (250 mL) were filtered through a 0.45 μm cellulose filter (Whatman, UK). The filtrate was kept frozen to be used for extracellular (dissolved) microcystins. The residue with trapped cells was frozen, extracted twice in 80% methanol, and centrifuged at 10,000 × *g* for 10 min. The supernatants were pooled together, and the organic solvent was blown with sterilized air. The aqueous fraction remaining after removing the organic solvent was filtered through GF/C filter paper and stored frozen until analysis. Concentrations of extracellular and intracellular microcystins were determined by high-performance liquid chromatography (HPLC) (Column, Nucleosil 5 C l ~ (150 × 4.6 mm)). The solvent system was: methanol – 0.05 M phosphate buffer (pH 3) (58:42). The flow rate was 1 $\mathrm{mL\,min^{-1}}$. Detection was at 238 nm (Harada *et al.* 1990).

Biochemical composition of the predominant phytoplankton in raw and treated waters

Proteins and lipids (% DW) of predominant species were estimated during winter and summer according to AOAC (2000) and carbohydrates were estimated spectrophotometry according to Dubois *et al.* (1956).

Chlorophyll-a – as a measure of phytoplankton biomass – was determined spectrophotometrically in 90% acetone extract of raw and treated waters according to Metzener *et al.* (1965) using the following equations:

$$\text{Chlorophyll-a} = 11.78(A_{663}) - 2.29(A_{647})$$

Concentrations of the heavy metals (Fe, Mn, Zn, Cu, Cr, Co, Cd, Ni, and Pb) in phytoplankton cells from raw and treated water were estimated seasonally by using a Perkin-Elmer 2380 atomic absorption spectrophotometer as described by Sudharsan *et al.* (2012).

Trophic state index

TSI of both raw and treated water samples were calculated using Chlorophyll-a concentration (Chl-a) in $\mu\mathrm{g\,L^{-1}}$ and the TP in $\mu g\,L^{-1}$ according to the formula of Lamparelli (2004) and CETESB (2009).

$$TSI_{(Chl\text{-}a)} = 10 \times \left(6 - \left\{\frac{0.92 - 0.34 \times \ln[\text{Chl-a}]}{\ln 2}\right\}\right)$$

$$TSI_{(TP)} = 10 \times \left(6 - \left\{\frac{1.77 - 0.42 \times \ln[\text{TP}]}{\ln 2}\right\}\right)$$

where ln is the natural logarithm. The TSI is the simple arithmetic average of the indices for Chl-a and TP.

$$TSI = \frac{TSI(\text{Chl-a}) + TSI(\text{TP})}{2}$$

The TSI values are distributed in five trophic state classes according to Lamparelli (2004) and CETESB (2009) as follows: $TSI < 40$ (oligotrophic); $40 \leq TSI < 50$ (mesotrophic); $50 \leq TSI < 60$ (meso-eutrophic); $60 \leq TSI < 80$ (eutrophic), and $TSI > 80$ (hypereutrophic).

Statistical analyses

Data were analyzed using two-way analysis of variance (ANOVA), followed by mean separation according to Duncan's multiple range test at $P < 0.05$. Two-tailed Pearson product-moment correlation was performed to examine the relationship between all physicochemical parameters, phytoplankton diversity, and microcystin concentrations. Statistical analysis was done using SPSS version 22.

RESULTS

Physicochemical properties of water

The effect of the main factors (water treatment and season) and their interaction was significant on most physicochemical parameters of water at a compact Kafr El-Shinawy treatment plant (Table 1). Table 2 summarizes the physicochemical characteristics of the raw and treated water at Kafr El-Shinawy treatment plant during 2018. The results showed significant seasonal variations in temperatures of both raw and treated water, which associated with marked alterations in some of the physicochemical characteristics of water. Water temperature ranged from 17.9 ± 2.48 to 31.0 ± 2.44 °C in raw water with a relative decrease in treated water ranging from 16.1 ± 1.59 to 29.4 ± 1.79 °C. Water temperature was correlated positively with EC ($r = 0.755$, $p < 0.01$), alkalinity ($r = 0.788$, $p < 0.01$), BOD ($r = 0.517$, $p < 0.01$), and pH ($r = 0.667$, $p < 0.01$). Water turbidity decreased from raw to treated water throughout the study period. The minimum values of turbidity in both raw (4.30 ± 0.38 NTU) and treated water (1.27 ± 0.12 NTU) were reported during winter. Water turbidity was correlated significantly with pH, alkalinity, DO, BOD, nutrients, and some heavy metals. As shown in Table 2, water pH values were generally on the alkaline side and ranged between 7.76 (during winter) and 8.51 (during summer) in raw water with lower values in treated water. In both raw and treated water, the maxima values of EC were in summer (Table 2). Throughout the four seasons, raw water recorded higher alkalinity compared with treated water and ranged from 147.0 ± 13.8 $mg\,L^{-1}$ in winter to 174.0 ± 17.3 $mg\,L^{-1}$ in summer. DO showed its higher concentrations in treated water (6.67–7.57 $mg\,L^{-1}$) than that in raw water (5.10–6.83 $mg\,L^{-1}$). It is also observed that DO in raw water increased by decreasing water temperature (significant negative correlation). On the contrary, BOD of both raw and treated water increased with increasing water temperature (significant positive correlation). BOD ranged from 2.71 to 3.81 $mg\,L^{-1}$ in raw water and from 1.51 to 2.23 $mg\,L^{-1}$ in treated water. Nitrogen forms (ammonia, nitrite, and nitrate), total nitrogen, total-P, and ortho-P were lower in raw water than in treated water and correlated significantly with BOD. Ortho-P and total-P in raw and treated water were in limited seasonal variability. Ortho-P values were very low in treated water, while total phosphorus has considerable values. Silica concentrations were higher in treated water than those in raw water and approached their maxima during winter (4.00 ± 0.34 $mg\,L^{-1}$ in treated water and 2.51 ± 0.52 $mg\,L^{-1}$ in raw water).

The effect of the main factors (water treatment and season) and their interaction on heavy metal concentrations of water was significant (Table 3). The effect of water treatment was stronger (with a higher *F* ratio) than that of a season for all determined heavy metals that decreased in treated water than that in raw water. Levels of all the measured heavy metals especially Mn, Zn, and Fe were

Table 1 | Two-way ANOVA showing the effect of the main factors (water treatment and season) and their interaction on physicochemical parameters of water at Kafr El-Shinawy drinking-water treatment plant – Damietta

Variable and treatment of variation	df	*F*	*P*	Variable and treatment of variation	df	*F*	*P*
Temperature				*Silica*			
Water treatment	1	1216.89	0.000	Water treatment	1	381.045	0.000
Season	3	23956.6	0.000	Season	3	576.301	0.000
Water treatment × season	3	75.704	0.000	Water treatment × season	3	208.962	0.000
Turbidity				*Ammonia*			
Water treatment	1	16419.6	0.000	Water treatment	1	13268.6	0.000
Season	3	306.935	0.000	Season	3	79.881	0.000
Water treatment × season	3	113.231	0.000	Water treatment × season	3	79.881	0.000
pH				*Nitrite*			
Water treatment	1	108.926	0.000	Water treatment	1	1216.00	0.000
Season	3	30.894	0.000	Season	3	59.368	0.000
Water treatment × season	3	1.6570	0.216	Water treatment × season	3	59.368	0.000
Conductivity				*Nitrate*			
Water treatment	1	0.1560	0.698	Water treatment	1	9130.08	0.000
Season	3	365.173	0.000	Season	3	20.306	0.000
Water treatment × season	3	0.7250	0.552	Water treatment × season	3	20.306	0.000
Total alkalinity				*Total-N*			
Water treatment	1	940.612	0.000	Water treatment	1	92852.0	0.000
Season	3	1681.57	0.000	Season	3	22.522	0.000
Water treatment × season	3	9.2190	0.001	Water treatment × season	3	22.522	0.000
DO				*Ortho-P*			
Water treatment	1	1315.09	0.000	Water treatment	1	13572.3	0.000
Season	3	181.031	0.000	Season	3	4.250	0.022
Water treatment × season	3	134.635	0.000	Water treatment × season	3	2.250	0.122
BOD				*Total-P*			
Water treatment	1	13489.7	0.000	Water treatment	1	3864.39	0.000
Season	3	988.937	0.000	Season	3	6.556	0.004
Water treatment × season	3	224.678	0.000	Water treatment × season	3	9.912	0.001

higher in phytoplankton cells than that in raw water and treated water (Table 4). Correlation between heavy metals and other physicochemical parameters of both raw and treated water is presented in Table 5. The results showed significant correlations between most of the metals at $p < 0.01$. Heavy metals Fe, Mn, Zn, Cd, Ni, and Pb were correlated positively with water turbidity. Mn, Zn, Cu, and Cd were correlated negatively with DO and positively with water pH and BOD. Heavy metals Fe, Zn, Cd, Ni, and Pb were correlated positively with nutrients (ammonia, nitrite, nitrate, total-N, total-P, and ortho-P). Also, positive correlations between some heavy metals (Mn and Zn) and water EC and alkalinity were reported.

The effect of the main factors (water treatment and season) and their interaction on THMs in raw and treated water was significant ($P < 0.05$) as shown in Table 6. The effect of water treatment was stronger (with a higher F ratio) than that of a season for all tested THMs. The present results showed that high values of THMs in water were during summer, whereas low concentrations were during winter, with an increase in treated water. The water treatment exhibited its maximum efficiency in winter. THMs specification

Table 2 | Seasonally variations in physicochemical characteristics (Mean ± standard error, $n = 3$) of raw and treated waters of Kafr El-Shinawy drinking-water treatment plant – Damietta

		Season			
Water characteristic	**Water treatment**	**Winter**	**Spring**	**Summer**	**Autumn**
Temperature (°C)	Raw water	17.9 ± 2.48^{b}	25.5 ± 2.54^{cd}	31.0 ± 2.44^{g}	26.0 ± 2.69^{e}
	Treated water	16.1 ± 1.59^{a}	25.0 ± 2.58^{c}	29.4 ± 1.79^{f}	25.1 ± 2.51^{c}
Turbidity (NTU)	Raw water	4.30 ± 0.38^{d}	6.01 ± 0.57^{f}	6.00 ± 0.57^{f}	5.04 ± 0.50^{e}
	Treated water	1.27 ± 0.12^{a}	1.50 ± 0.15^{b}	1.86 ± 0.18^{c}	1.34 ± 0.13^{a}
pH	Raw water	7.76 ± 0.91^{d}	8.12 ± 0.81^{g}	8.51 ± 0.75^{h}	7.90 ± 0.79^{ef}
	Treated water	7.34 ± 0.72^{a}	7.58 ± 0.75^{bc}	7.86 ± 0.78^{e}	7.53 ± 0.74^{b}
Conductivity ($dS\ m^{-1}$)	Raw water	540.0 ± 35.0^{a}	600.7 ± 60.1^{e}	750.0 ± 73.3^{f}	550.3 ± 34.7^{b}
	Treated water	550.0 ± 51.1^{b}	590.3 ± 58.1^{d}	755.0 ± 73.9^{g}	554.0 ± 54.5^{bc}
Total alkalinity ($mg\ L^{-1}$)	Raw water	147.0 ± 13.8^{c}	162.0 ± 16.0^{e}	174.0 ± 17.3^{g}	147.3 ± 14.4^{bc}
	Treated water	136.1 ± 13.1^{a}	151.3 ± 14.8^{d}	164.7 ± 16.3^{ef}	140.3 ± 14.0^{b}
DO ($mg\ L^{-1}$)	Raw water	6.83 ± 0.61^{e}	6.09 ± 0.58^{b}	5.10 ± 0.50^{a}	6.20 ± 0.59^{c}
	Treated water	7.10 ± 0.71^{g}	7.57 ± 0.74^{h}	6.67 ± 0.67^{d}	7.00 ± 0.64^{f}
BOD ($mg\ L^{-1}$)	Raw water	2.71 ± 0.27^{e}	2.99 ± 0.29^{f}	3.81 ± 0.32^{h}	3.50 ± 0.35^{g}
	Treated water	1.51 ± 0.15^{a}	2.00 ± 0.18^{c}	2.23 ± 0.22^{d}	1.71 ± 0.17^{b}
Silica ($mg\ L^{-1}$)	Raw water	2.51 ± 0.52^{c}	3.10 ± 0.30^{d}	3.60 ± 0.31^{f}	2.23 ± 0.22^{a}
	Treated water	4.00 ± 0.34^{h}	3.30 ± 0.32^{e}	3.67 ± 0.35^{fg}	2.33 ± 0.22^{b}
Ammonia ($mg\ L^{-1}$)	Raw water	0.42 ± 0.038^{f}	0.35 ± 0.034^{d}	0.28 ± 0.021^{c}	0.39 ± 0.038^{e}
	Treated water	0.02 ± 0.001^{ab}	0.01 ± 0.001^{a}	0.01 ± 0.001^{a}	0.01 ± 0.001^{a}
Nitrite ($mg\ L^{-1}$)	Raw water	0.20 ± 0.015^{g}	0.09 ± 0.008^{de}	0.08 ± 0.007^{d}	0.12 ± 0.011^{f}
	Treated water	0.05 ± 0.003^{c}	0.01 ± 0.002^{a}	0.01 ± 0.002^{a}	0.03 ± 0.004^{b}
Nitrate ($mg\ L^{-1}$)	Raw water	0.31 ± 0.031^{h}	0.27 ± 0.026^{g}	0.24 ± 0.023^{e}	0.28 ± 0.028^{f}
	Treated water	0.20 ± 0.003^{d}	0.15 ± 0.002^{c}	0.09 ± 0.002^{ab}	0.08 ± 0.002^{a}
Total-N ($mg\ L^{-1}$)	Raw water	2.72 ± 0.270^{d}	2.74 ± 0.272^{de}	2.91 ± 0.223^{g}	2.76 ± 0.275^{def}
	Treated water	0.19 ± 0.009^{c}	0.11 ± 0.003^{a}	0.20 ± 0.004^{c}	0.15 ± 0.004^{b}
Ortho-P ($mg\ L^{-1}$)	Raw water	0.021 ± 0.005^{cd}	0.020 ± 0.002^{c}	0.020 ± 0.002^{c}	0.020 ± 0.002^{c}
	Treated water	0.006 ± 0.0001^{ab}	0.005 ± 0.0001^{a}	0.006 ± 0.0001^{ab}	0.006 ± 0.0001^{ab}
Total-P ($mg\ L^{-1}$)	Raw water	1.70 ± 0.13^{d}	1.82 ± 0.178^{ef}	1.99 ± 0.21^{g}	1.80 ± 0.22^{e}
	Treated water	0.50 ± 0.056^{b}	0.50 ± 0.055^{b}	0.52 ± 0.057^{bc}	0.45 ± 0.050^{a}

Values with different letters 'a, b, c, d, e, f, …' are significantly different at $P < 0.05$.

shows that their presence in both raw and treated water was in the order: chloroform > dichlorobromomethane > dibromochloromethane. As shown in Figure 1, chloroform concentrations in raw and treated water were in the range of 2.79–17.43 to 18.42–69.75 $mg\ L^{-1}$, respectively. The results showed significant variations in dichlorobromomethane in raw and treated water ($P < 0.05$) ranging from 1.52 $mg\ L^{-1}$ (in raw water during winter) to 48.36 $mg\ L^{-1}$ (in treated water during summer). The maximum concentration of dibromochloromethane was 25.98 $mg\ L^{-1}$ in treated water during summer. Moreover, THMs correlated negatively with nutrients in both the native and treated water. THMs levels in both raw and treated water were correlated positively with silica and extramicrocystin and negatively with TSI, phytoplankton number, and ortho-P.

Phytoplankton composition

Three phytoplankton groups were found in raw and treated waters, viz. Cyanophyta, Chlorophyta, and Bacillariophyta. The phytoplankton density in treated water was much less than those in raw water. The effect of the main factors (water treatment and season) and their interaction on the phytoplankton community at the study area was significant ($P < 0.05$) as shown in Table 6. The effect of water treatment was stronger (with a higher F ratio) than that of a season for

Table 3 | Two-way ANOVA showing the effect of the main factors (water treatment and season) and their interaction on heavy metals concentrations of raw and treated waters at Kafr El-Shinawy drinking-water treatment plant – Damietta

Variable and treatment of variation	df	*F*	*P*	Variable and treatment of variation	df	*F*	*P*
Fe				*Co*			
Water treatment	1	94848.0	0.000	Water treatment	1	1366561	0.000
Season	3	118.327	0.000	Season	3	84521.0	0.000
Water treatment × season	3	130.171	0.000	Water treatment × season	3	70721.0	0.000
Mn				*Cd*			
Water treatment	1	3910.10	0.000	Water treatment	1	2726112	0.000
Season	3	51.391	0.000	Season	3	12703.2	0.000
Water treatment × season	3	9.1420	0.001	Water treatment × season	3	12503.2	0.000
Zn				*Ni*			
Water treatment	1	41538.8	0.000	Water treatment	1	84807.7	0.000
Season	3	97.835	0.000	Season	3	2718.66	0.000
Water treatment × season	3	365.482	0.000	Water treatment × season	3	2009.74	0.000
Cu				*Pb*			
Water treatment	1	3087049	0.000	Water treatment	1	2910436	0.000
Season	3	135273	0.000	Season	3	5660.00	0.000
Water treatment × season	3	75513.0	0.000	Water treatment × season	3	6620.00	0.000
Cr							
Water treatment	1	15987.0	0.000				
Season	3	677.667	0.000				
Water treatment × season	3	197.667	0.000				

only cell number of Cyanophyta; meanwhile, the effect of season was stronger on both Chlorophyta and Bacillariophyta numbers.

The phytoplankton community of raw water was composed mainly of Cyanophyta which contributed up to 67.80% of the total cell number during spring, summer (91.74%), autumn (69.75%), and winter (14.04%); followed by Bacillariophyta, which represents 16.48% during spring, summer (4.96%), autumn (25.70%), and winter (77.93%). Meanwhile, Chlorophyta in raw water represents 15.75% of the total cell number during spring, summer (3.31%), autumn (4.55%), and winter (8.03%). In treated water, Chlorophyta was the predominant phytoplankton group which contributed 61.95% during winter, spring (82.35%), and autumn (22.58%) of the total cell number, with no detection during summer (Figure 2). Cyanophyta ranked the second position of dominance with cell number of 13.53% during spring, (77.78%) during summer, and (48.39%) during autumn of the total cell number with no detection during winter. While Bacillariophyta in treated water represents 4.12% during spring, summer (22.22%), autumn (29.03%), and winter (38.05%).

The maximum cell numbers of phytoplankton were found in raw water during summer (55.5×10^7 cell L^{-1}). The species composition of raw water (47 taxa) was richer than that of treated water (only 15 taxa). During winter, *Oscillatoria limnetica* was predominated in raw water (98.5% total phytoplankton). Meanwhile, *Microcystis aeruginosa* predominated during summer (57.5%). Other Cyanophyta species also coexisted but in low numbers (Table 7). *Pediastrum simplex* was the predominant Chlorophyta in raw water throughout the year. In raw water, *Melosira granulata* predominated Bacillariophyta during winter and autumn, while *Cyclotella meneghiniana* and *Diatoma elongatum* were the predominant Bacillariophyta during spring and summer, respectively. In treated water, some Chlorophyta and Bacillariophyta coexisted in low numbers.

Table 4 | Seasonally variations in concentrations of some heavy metals (Mean ± standard error, $n = 3$) in raw and treated waters, and phytoplankton cells Kafr El-Shinawy drinking-water treatment plant – Damietta

		Season			
Heavy metal	**Treatment**	**Winter**	**Spring**	**Summer**	**Autumn**
		Water			
Fe (mg L^{-1})	Raw	0.097 ± 0.0048^{de}	0.120 ± 0.0060^{g}	0.100 ± 0.0050^{def}	0.094 ± 0.0047^{d}
	Treated	0.060 ± 0.0030^{c}	0.051 ± 0.0026^{b}	0.040 ± 0.0020^{a}	0.060 ± 0.0030^{c}
Mn (mg L^{-1})	Raw	0.067 ± 0.0034^{g}	0.057 ± 0.0029^{e}	0.070 ± 0.0035^{h}	0.061 ± 0.0031^{f}
	Treated	0.014 ± 0.0007^{ab}	0.020 ± 0.0010^{c}	0.030 ± 0.0015^{d}	0.010 ± 0.0005^{a}
Zn (mg L^{-1})	Raw	0.037 ± 0.0019^{g}	0.032 ± 0.0016^{def}	0.030 ± 0.0015^{de}	0.029 ± 0.0015^{d}
	Treated	0.020 ± 0.0010^{c}	0.016 ± 0.0008^{ab}	0.020 ± 0.0010^{c}	0.015 ± 0.0008^{a}
Cu (mg L^{-1})	Raw	0.021 ± 0.0011^{d}	0.025 ± 0.0025^{ef}	0.024 ± 0.0012^{e}	0.027 ± 0.0014^{g}
	Treated	0.004 ± 0.0002^{a}	0.004 ± 0.0002^{a}	0.010 ± 0.0005^{c}	0.005 ± 0.0003^{ab}
Cr (mg L^{-1})	Raw	0.005 ± 0.0003^{c}	0.005 ± 0.0005^{c}	0.005 ± 0.0003^{c}	0.006 ± 0.0003^{d}
	Treated	0.002 ± 0.0001^{a}	0.002 ± 0.0001^{a}	0.002 ± 0.0001^{a}	0.003 ± 0.0002^{b}
Co (mg L^{-1})	Raw	0.020 ± 0.0010^{d}	0.020 ± 0.0020^{d}	0.024 ± 0.0012^{e}	0.020 ± 0.0010^{d}
	Treated	0.009 ± 0.0005^{ab}	0.010 ± 0.0005^{c}	0.010 ± 0.0005^{c}	0.008 ± 0.0004^{a}
Cd (mg L^{-1})	Raw	0.040 ± 0.0020^{f}	0.030 ± 0.0030^{e}	0.026 ± 0.0013^{d}	0.022 ± 0.0011^{c}
	Treated	0.003 ± 0.0002^{a}	0.004 ± 0.0002^{ab}	0.004 ± 0.0002^{ab}	0.003 ± 0.0002^{a}
Ni (mg L^{-1})	Raw	0.018 ± 0.0009^{e}	0.021 ± 0.0011^{fg}	0.022 ± 0.0022^{h}	0.020 ± 0.0020^{f}
	Treated	0.008 ± 0.0004^{c}	0.007 ± 0.0004^{ab}	0.006 ± 0.0003^{a}	0.013 ± 0.0007^{d}
Pb (mg L^{-1})	Raw	0.021 ± 0.0011^{d}	0.022 ± 0.0011^{de}	0.022 ± 0.0022^{de}	0.019 ± 0.0019^{c}
	Treated	0.005 ± 0.0003^{ab}	0.004 ± 0.0002^{a}	0.004 ± 0.0002^{a}	0.004 ± 0.0002^{a}
		Phytoplankton			
Fe (mg L^{-1})	Raw	0.910 ± 0.0455^{d}	1.020 ± 0.0510^{g}	0.980 ± 0.0490^{f}	0.950 ± 0.0475^{e}
	Treated	0.320 ± 0.0160^{c}	0.320 ± 0.0160^{c}	0.250 ± 0.0125^{a}	0.270 ± 0.0135^{ab}
Mn (mg L^{-1})	Raw	0.550 ± 0.0275^{e}	0.450 ± 0.0225^{d}	0.600 ± 0.0180^{g}	0.560 ± 0.0280^{ef}
	Treated	0.090 ± 0.0500^{b}	0.090 ± 0.0045^{b}	0.160 ± 0.0080^{c}	0.076 ± 0.0038^{a}
Zn (mg L^{-1})	Raw	0.350 ± 0.0175^{g}	0.300 ± 0.0150^{f}	0.280 ± 0.0140^{e}	0.280 ± 0.0140^{e}
	Treated	0.050 ± 0.0045^{ab}	0.045 ± 0.0023^{a}	0.080 ± 0.0040^{d}	0.070 ± 0.0035^{c}
Cu (mg L^{-1})	Raw	0.110 ± 0.0055^{e}	0.160 ± 0.0160^{f}	0.200 ± 0.0100^{g}	0.230 ± 0.0115^{h}
	Treated	0.020 ± 0.0025^{b}	0.016 ± 0.0008^{a}	0.050 ± 0.0025^{d}	0.028 ± 0.0014^{c}
Cr (mg L^{-1})	Raw	0.025 ± 0.0013^{d}	0.030 ± 0.0030^{e}	0.033 ± 0.0017^{f}	0.036 ± 0.0018^{g}
	Treated	0.012 ± 0.0010^{ab}	0.010 ± 0.0005^{a}	0.010 ± 0.0005^{a}	0.018 ± 0.0009^{c}
Co (mg L^{-1})	Raw	0.120 ± 0.0060^{c}	0.120 ± 0.0120^{c}	0.210 ± 0.0105^{c}	0.180 ± 0.0090^{d}
	Treated	0.050 ± 0.0006^{a}	0.070 ± 0.0035^{b}	0.070 ± 0.0035^{b}	0.050 ± 0.0025^{a}
Cd (mg L^{-1})	Raw	0.250 ± 0.0125^{f}	0.200 ± 0.0200^{d}	0.220 ± 0.0110^{e}	0.190 ± 0.0095^{c}
	Treated	0.020 ± 0.0025^{a}	0.020 ± 0.0010^{a}	0.021 ± 0.0011^{ab}	0.020 ± 0.0010^{a}
Ni (mg L^{-1})	Raw	0.090 ± 0.0045^{e}	0.120 ± 0.0060^{f}	0.150 ± 0.0150^{h}	0.140 ± 0.0140^{g}
	Treated	0.040 ± 0.0010^{bc}	0.022 ± 0.0011^{a}	0.039 ± 0.0020^{b}	0.050 ± 0.0025^{d}
Pb (mg L^{-1})	Raw	0.180 ± 0.0090^{g}	0.170 ± 0.0085^{f}	0.160 ± 0.0320^{e}	0.150 ± 0.0300^{d}
	Treated	0.024 ± 0.0020^{bc}	0.020 ± 0.0010^{a}	0.023 ± 0.0012^{b}	0.024 ± 0.0012^{bc}

Values with different letters 'a, b, c, d, e, f, …' are significantly different at $P < 0.05$.

Pearson's correlation coefficient revealed that the composition of the phytoplankton community depends on the physicochemical parameters of water, which in turn depends on water treatment and seasons. As shown in Table 8, a significant negative correlation was reported between Bacillariophyta cell numbers and both silica ($r = -0.356$, $P < 0.01$).

Table 5 | Pearson's correlation between physicochemical parameters at intake and output of Kafr El-Shinawy drinking-water treatment plant – Damietta

	Temperature	Turbidity	pH	EC	Alkalinity	DO	BOD	Si	Ammonia	Nitrite	Nitrate	Total-N	Ortho-P	Total-P	Fe	Mn	Zn	Cu	Cr	Co	Cd	Ni	Pb
Temperature	1																						
Turbidity	0.319	1																					
pH	0.667**	**0.818****	1																				
EC	0.755**	0.175	0.600**	1																			
Alkalinity	0.788**	**0.574****	0.859**	0.858**	1																		
DO	**0.502***	**0.860****	**0.871****	**0.437***	**0.650****	1																	
BOD	0.517**	**0.929****	**0.866****	0.337	0.655**	**0.870****	1																
Si	0.032	**0.224**	0.037	0.545**	0.323	0.004	**0.222**	1															
Ammonia	0.015	0.906**	0.584**	**0.141**	0.269	**0.638****	0.818**	**0.469***	1														
Nitrite	**0.190**	0.728**	0.397	**0.238**	0.114	**0.424***	0.643**	**0.511***	0.928**	1													
Nitrate	0.051	0.930**	0.633**	**0.085**	0.325	**0.686****	0.842**	**0.423***	0.996**	0.916**	1												
Total-N	0.150	0.968**	0.718**	0.014	0.415*	**0.780****	0.899**	**0.354**	0.974**	0.864**	0.988**	1											
Ortho-P	0.113	0.959**	0.689**	**0.010**	0.394	**0.747****	0.882**	0.356	0.983**	0.883**	0.993**	0.998**	1										
Total-P	0.188	0.969**	0.717**	0.029	0.417*	**0.794****	0.919**	**0.353**	0.965**	0.832**	0.976**	0.993**	0.989**	1									
Fe	0.132	0.477*	0.020	**0.644****	**0.230**	**0.115**	0.202	**0.349**	0.585**	0.499*	0.566**	0.517**	0.534**	0.499*	1								
Mn	0.195	0.744**	0.906**	0.701**	0.818**	**0.915****	0.851**	0.119	0.511*	0.361	0.564**	0.661**	0.631**	0.671**	**0.205**	1							
Zn	0.062	0.597**	0.540**	0.313	0.395	**0.696****	0.649**	0.158	0.561**	0.555**	0.596**	0.635**	0.631**	0.635**	0.054	0.721**	1						
Cu	0.385	0.372	0.656**	0.667**	0.640**	**0.637****	0.604**	**0.108**	0.138	**0.040**	0.169	0.264	0.221	0.306	**0.483***	0.760**	0.293	1					
Cr	0.265	0.088	**0.113**	**0.369**	**0.149**	0.128	0.055	**0.459***	0.087	**0.050**	0.061	0.050	0.044	0.089	0.494*	**0.292**	**0.553****	**0.956****	1				
Co	0.440*	0.121	0.194	0.326	0.213	**0.203**	0.125	0.381	0.172	0.368	0.202	0.202	0.214	0.153	0.901**	0.381	0.683*	**0.087**	**0.857****	1			
Cd	0.062	0.930**	0.632**	**0.018**	0.398	**0.701****	0.808**	**0.311**	0.920**	0.796**	0.936**	0.938**	0.938**	0.926**	0.112	0.565**	0.503*	0.183	0.195	0.103	1		
Ni	0.335	0.672**	0.319	**0.268**	0.154	0.350	0.409*	**0.114**	0.676**	0.579**	0.685**	0.666**	0.678**	0.639**	0.851**	0.134	0.180	**0.295**	0.312	**0.029**	0.777**	1	
Pb	0.071	0.464*	0.137	**0.320**	**0.035**	**0.075**	0.391	**0.524****	0.670**	0.721**	0.632**	0.562**	0.586**	0.569**	0.521**	0.026	0.087	**0.140**	0.360	**0.023**	0.557**	0.504*	1

**Statistically significant correlation at $p < 0.01$, *Statistically, significant correlation at $p < 0.05$.

Bold numbers indicate a negative correlation.

Table 6 | Two-way ANOVA showing the effect of the main factors (water treatment and seasons) and their interaction on THMs levels, phytoplankton diversity, microcystin concentrations, Chlorophyll-a of phytoplankton, and TSI values in the water at Kafr El-Shinawy drinking-water treatment plant – Damietta

Variable and treatment of variation	df	*F*	*P*	Variable and treatment of variation	df	*F*	*P*
Chloroform				*Bacillariophyta (cell number)*			
Water treatment	1	17443729	0.000	Water treatment	1	116079.7	0.000
Season	3	4172580	0.000	Season	3	881887.5	0.000
Water treatment × season	3	1427454	0.000	Water treatment × season	3	280940.1	0.000
Dichlorobromomethane				*Intramicrocystin concentrations*			
Water treatment	1	719773777	0.000	Water treatment	1	2910.82	0.000
Season	3	190202800	0.000	Season	3	137.260	0.000
Water treatment × season	3	63348845	0.000	Water treatment × season	3	134.908	0.000
Dibromochloromethane				*Extramicrocystin concentrations*			
Water treatment	1	195832036	0.000	Water treatment	1	11184.8	0.000
Season	3	50480612	0.000	Season	3	2138.21	0.000
Water treatment × season	3	16022276	0.000	Water treatment × season	3	194.464	0.000
Cyanophyta (cell number)				*Phytoplankton chlorophyll-a*			
Water treatment	1	10630415	0.000	Water treatment	1	22814.1	0.000
Season	3	1693782	0.000	Season	3	5920.19	0.000
Water treatment × season	3	1461754	0.000	Water treatment × season	3	4592.06	0.000
Chlorophyta (cell number)				*TSI*			
Water treatment	1	2898449	0.000	Water treatment	1	2278690	0.000
Season	3	4172580	0.000	Season	3	92465.6	0.000
Water treatment × season	3	6563210	0.000	Water treatment × season	3	16304.8	0.000

Intracellular and extracellular microcystins

The effect of the main factors (water treatment and season) and their interaction on the levels of intracellular and extracellular microcystin was significant ($P < 0.05$) with a higher effect of water treatment (higher *F* ratio) than that of a season (Table 6). Both intracellular and extracellular (dissolved) microcystins recorded their higher concentrations during summer. Throughout the study period, the intracellular microcystin levels were lower in treated water than in raw water. In raw water, the lowest intracellular microcystin was obtained during winter ($0.71\ \mu g\ L^{-1}$), while the highest concentration was $1.70\ \mu g\ L^{-1}$ during summer (Table 9). The maximum concentration of dissolved microcystins in raw water ($1.30\ \mu g\ L^{-1}$) was lower than that in treated water ($2.01\ \mu g\ L^{-1}$) during summer. Also, the minimum concentration of dissolved microcystins in raw water ($0.56\ \mu g\ L^{-1}$) during winter was lower than that in treated water ($1.00\ \mu g\ L^{-1}$) during autumn.

Biochemical composition of the predominant phytoplankton species in raw and treated water

Biochemical constituents of the predominant species in raw water *O. limnetica* and *M. aeruginosa* were estimated during winter and summer, respectively (Figure 3). Protein, lipid, and carbohydrates were significantly different between the two species. *M. aeruginosa* was richer in protein (47.00% DW) and lipid (4.28% DW) than *O. limnetica* (40.40 and 3.20% DW, respectively). By contrast, total carbohydrate was higher in *O. limnetica* (29.60% DW) than *M. aeruginosa* (21.60% DW).

The effect of the main factors (water treatment and season) and their interaction on chlorophyll-a content of

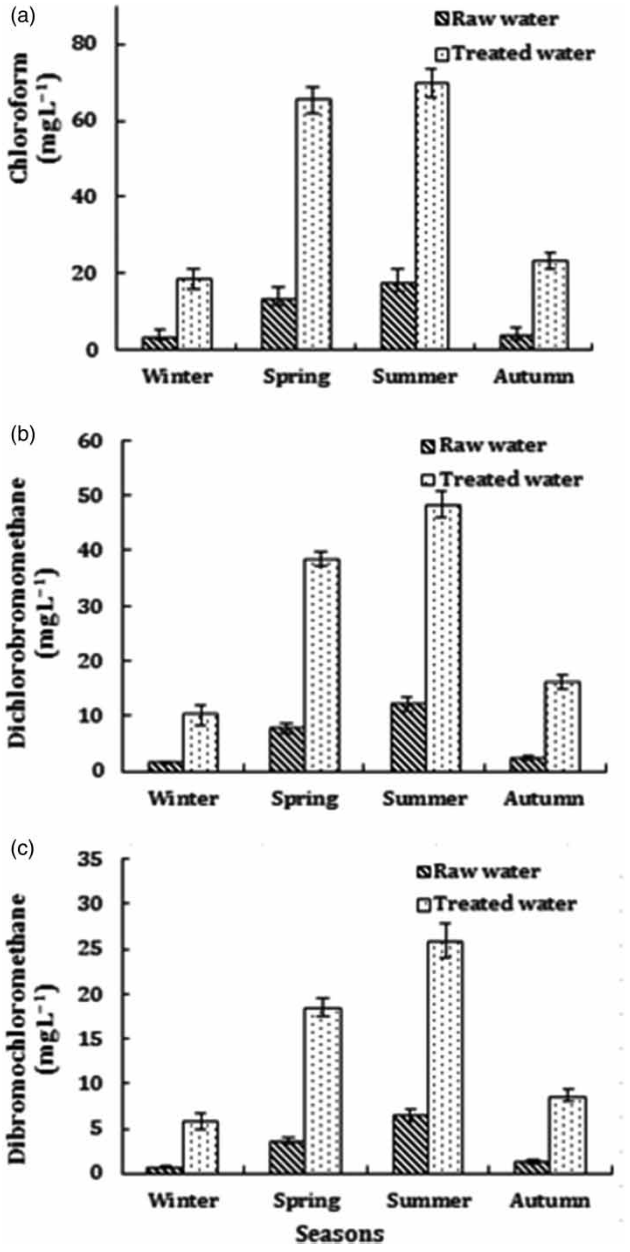

Figure 1 | Concentrations of (a) chloroform, (b) dichlorobromomethane, and (c) dibromochloromethane in raw and treated water of Kafr El-Shinawy drinking-water treatment plant – Damietta. Values are means of three replicates ± SE.

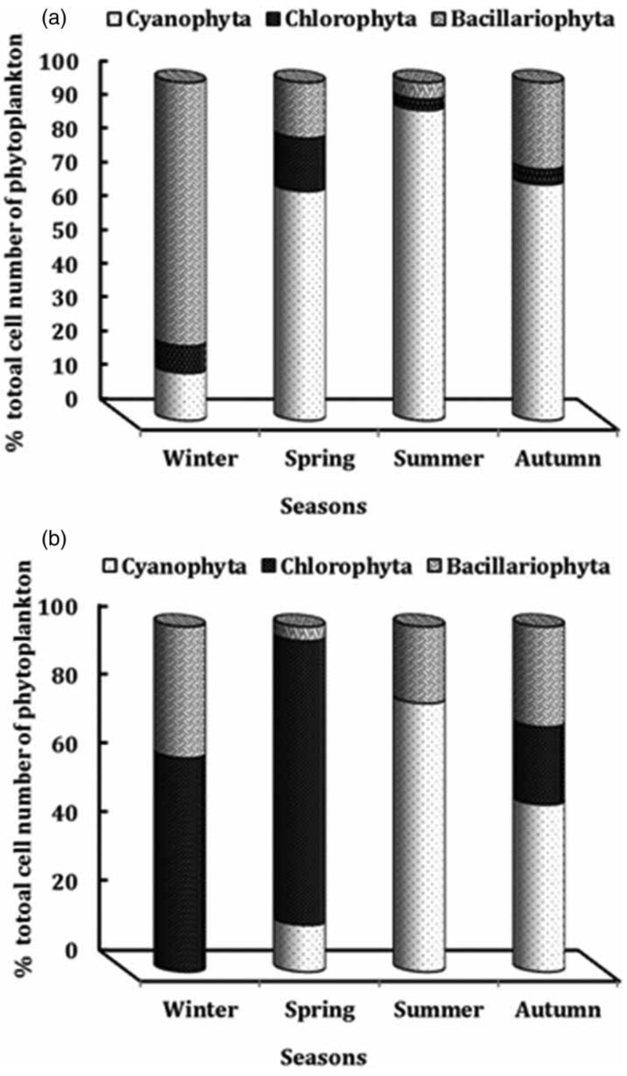

Figure 2 | Seasonal variations in percentage of cell numbers of different phytoplankton groups in (a) raw and (b) treated water of Kafr El-Shinawy treatment plant – Damietta.

phytoplankton of raw and treated water was very highly significant ($P < 0.05$) with a higher effect of water treatment than that of a season (Table 6). The chlorophyll-a content in phytoplankton was significantly higher in raw water than in treated water during the study period ($P < 0.01$), particularly during spring (Figure 4). Chlorophyll-a content was generally highest during summer (1.42 $\mu g\ L^{-1}$), followed by spring (1.21 $\mu g\ L^{-1}$), while the lowest values were during winter (0.04 $\mu g\ L^{-1}$).

Trophic state index

The ANOVA results showed that the effect of the main factors (water treatment and season) and their interaction on the TSI values of the water samples were significantly different ($P < 0.05$). The effect of water treatment on TSI values was stronger (with a higher *F* ratio) than that of a season (Table 6). The trophic state classifications of water samples

Table 7 | Seasonally variation in the cell number (cell × 10^5 L^{-1}) of the different phytoplankton groups at the intake and output of Kafr El-Shinawy drinking-water treatment plant – Damietta

	Winter		Spring		Summer		Autumn	
Phytoplankton group	**Intake**	**Output**	**Intake**	**Output**	**Intake**	**Output**	**Intake**	**Output**
Cyanophyta								
Anabaena circinalis	–	–	116	–	188	–	32	–
A. variabilis	–	–	112	–	178	–	28	–
A. constricta	–	–	97	–	168	–	23	–
Aphanizomenon flos aquae	5	–	1,485	–	3,919	–	860	–
Chroococcus limneticus	–	–	1,182	–	1,867	–	885	–
Coelosphaerium kuetzinglanum	–	–	30	–	80	–	10	–
Gloeocapsa aeruginosa	–	–	1,185	0.06	2,441	0.2	466	0.05
Gomphosphaeria lacustris	6	–	1,566	–	3,958	–	809	–
Merismopedia glauca	4	–	606	–	971	–	30	–
M. elegans	–	–	499	–	602	–	25	–
M. incerta	–	–	456	–	872	–	28	–
M. aeruginosa	10	–	5,828	0.17	29,314	0.5	10,416	0.1
Nostoc linckia	–	–	222	–	973	–	63	–
N. spongiaeforme	–	–	205	–	932	–	65	–
N. punctiforme	3	–	1,800	–	1,600	–	660	–
Oscillatoria agardhii	–	–	800	–	2,000	–	1,200	–
O. limnetica	1,900	–	700	–	200	–	300	–
Phormidium corium	–	–	419	–	693	–	250	–
Chlorophyta								
Actinastrum hantzschii	44	–	200	–	133	–	88	–
Ankistrodesmus angustus	50	–	140	–	40	–	31	–
Botryococcus braunii	31	–	180	–	77	–	37	–
Chlamydomonas spp.	52	–	171	–	93	–	83	–
Chlorella vulgaris	31	–	154	0.1	96	–	53	0.07
Coelastrum microporum	36	–	161	–	81	–	45	–
Dictyosphaerium pulchellum H. C. Wood	109	–	592	–	157	–	33	–
Oocystis marssonii	45	–	393	–	236	–	67	–
Pandorina morum	17	–	180	–	100	–	80	–
Pediastrum clathratum	10	–	164	–	90	–	56	–
P. duplex	65	–	186	–	133	–	129	–
P. simplex	510	0.3	1,078	0.6	393	–	273	–
Scenedesmus dimorphus	37	0.4	187	0.7	80	–	10	–
Staurastrum rotula Nordstedt	45	–	106	–	83	–	59	–
Ulothrix subitllssima	20	–	130	–	44	–	10	–
Bacillariophyta								
Amphora coffeaeformis	157	–	69	–	72	–	115	–
C. meneghiniana	1,827	–	783	–	347	–	907	–

(*continued*)

Table 7 | continued

	Winter		**Spring**		**Summer**		**Autumn**	
Phytoplankton group	**Intake**	**Output**	**Intake**	**Output**	**Intake**	**Output**	**Intake**	**Output**
Cyclotella spp.	600	0.2	504	–	302	–	405	–
D. elongatum	830	–	207	–	377	–	420	–
Fragilaria capucina	183	–	37	–	38	–	127	–
F. cortonensis	242	–	72	–	10	–	128	–
M. granulata	1,931	–	688	–	370	–	923	–
N. radiosa	923	–	243	–	253	0.2	300	–
Nitzschia palea	200	–	104	0.07	0	–	191	0.09
N. vermicularis	631	0.03	301	–	246	–	522	–
Stephanodiscus dubius	1,502	–	404	–	250	–	805	–
Synedra acus	706	0.2	480	–	340	–	544	–
S. ulna	800	–	250	–	120	–	480	–
S. gracillies	166	–	67	–	29	–	83	-

at Kafr El-Shinawy treatment plant based on TSI show a meso-eutrophic state in raw water samples during summer (TSI $= 50.53$) and spring (TSI $= 50.13$), a mesotrophic state in raw water samples during winter (TSI $= 47.82$) and autumn (TSI $= 46.72$), and in treated water samples during summer (TSI $= 40.75$). While the treated water was oligotrophic in winter (TSI $= 33.19$), spring (TSI $= 37.13$), and autumn (TSI $= 34.73$) (Table 10). The maximum TSI values of both raw (50.53) and treated water (40.75) were recorded during summer. TSI values were correlated positively with ortho-P, and both Cyanophyta and Chlorophyta numbers and negatively with chloroform, dichlorobromomethane, and dibromochloromethane.

DISCUSSION

Evaluation of the efficiency of water treatment regimes, in terms of the alteration in the physicochemical characteristics of water before and after treatment, is essential for a recommendation of water usage for drinking and other domestic purposes (Sarkar *et al.* 2020). The present work revealed that raw water at Kafr El-Shinawy drinking-water treatment plant is meso-eutrophic with a high load of nutrients and silica, along with a slightly alkaline pH (7.76–8.51) and low DO (5.10–6.83 mg L^{-1}) levels. Water temperature was correlated positively with EC ($r = 0.755$, $p < 0.01$), alkalinity ($r = 0.788$, $p < 0.01$), BOD ($r = 0.517$, $p < 0.01$), and temperature ($r = 0.667$, $p < 0.01$). These correlations agreed with that obtained by Sharma *et al.* (2008) and Shehata & Badr (2010). The present result indicated that the increase in temperature of raw water associated with a slight alkaline pH during summer stimulates phytoplankton growth especially Cyanophyta. In the present study, the positive correlations between water temperature and both pH ($r = 0.667$, $p < 0.01$) and alkalinity ($r = 0.788$, $p < 0.01$) were due to increased photosynthesis rate (high phytoplankton numbers) with increasing temperature and thus increasing pH value and water alkalinity. Variations in water temperature have been reported to strongly affect the composition, bioactivity, and growth of phytoplankton community (Rasconi *et al.* 2017).

Water turbidity was significantly correlated with nutrient concentrations (ammonia, nitrite, nitrate, total nitrogen, ortho-P, and total-P) in water. The high turbidity of raw water (4.30–6.01 NTU) compared with treated water (1.27–1.86 NTU) might be related to high organic pollution of raw water and the efficiency of water treatment. Water pH is an important factor in the aquatic system that directly affects the phytoplankton community. In the present study, the slight increase in raw water pH might be due to biological activity such as photosynthesis and

Table 8 | Pearson's correlation coefficients between trophic state of water (TSI), silica, ortho-P, THMs levels, phytoplankton numbers, and microcystin concentration at the intake and output of Kafr El-Shinawy drinking-water treatment plant – Damietta

	TSI	Silica	Ortho-P	Chloroform	Dichlorobromomethane	Dibromochloromethane	Cyanophyta number	Chlorophyta number	Bacillariophyta number	Intramicrocystin	Extramicrocystin
TSI	1										
Silica	**0.221**	1									
Ortho-P	0.937**	**0.356**	1								
Chloroform	**0.450***	0.466*	**0.704****	1							
Dichlorobromomethane	**0.419***	0.450*	**0.689****	0.993**	1						
Dibromochloromethane	**0.423***	0.465*	**0.696****	0.981**	0.997**	1					
Cyanophyta number	0.583**	**0.062**	0.384	**0.003**	**0.080***	0.107	1				
Chlorophyta number	0.670**	0.344	**0.582****	0.365	**0.260***	0.212	**0.745****	1			
Bacillariophyta number	0.017	**0.356****	0.194	**0.470***	**0.454***	**0.431***	**0.496***	**0.209**	1		
Intramicrocystin	0.886**	0.838**	0.393	**0.111**	−0.097	**0.097**	0.382	**0.259**	**0.222**	1	
Extramicrocystin	**0.551****	**0.176**	**0.768****	0.924**	0.935**	0.942**	0.087	0.303	0.521**	**0.504***	1

**Statistically significant correlation at $p < 0.01$, *Statistically, significant correlation at $p < 0.05$.

Bold numbers indicate a negative correlation.

Table 9 | Seasonally variations in concentrations (µg L^{-1}) of intracellular and extracellular microcystins (Mean ± standard error, $n = 3$) in raw and treated waters at Kafr El-Shinawy drinking-water treatment plant – Damietta

		Season			
Microcystin	**Treatment**	**Winter**	**Spring**	**Summer**	**Autumn**
Intracellular microcystin	Raw	0.710 ± 0.0284^{d}	0.980 ± 0.0392^{f}	1.700 ± 0.0680^{g}	0.880 ± 0.0352^{e}
	Treated	0.009 ± 0.0003^{b}	0.009 ± 0.0003^{b}	0.011 ± 0.0003^{bc}	0.003 ± 0.0001^{a}
Extracellular microcystin	Raw	0.560 ± 0.0168^{a}	0.680 ± 0.0340^{b}	1.300 ± 0.0520^{f}	0.740 ± 0.0518^{c}
	Treated	1.210 ± 0.0242^{e}	1.780 ± 0.0890^{g}	2.010 ± 0.1005^{h}	1.000 ± 0.0400^{d}

Values with different letters 'a, b, c, d, e, f, …' are significantly different at $P < 0.05$.

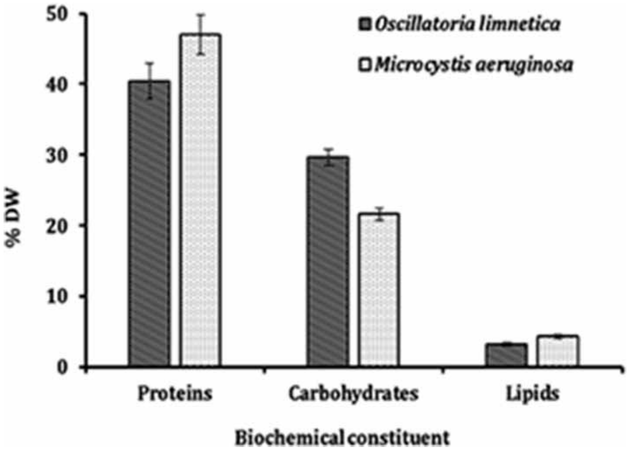

Figure 3 | Variations in concentrations of some biochemical constituents (% DW) of *O. limnetica* in winter and *M. aeruginosa* in summer, respectively, in raw water at Kafr El-Shinawy drinking-water treatment plant – Damietta. Values are means of three replicates ± SE.

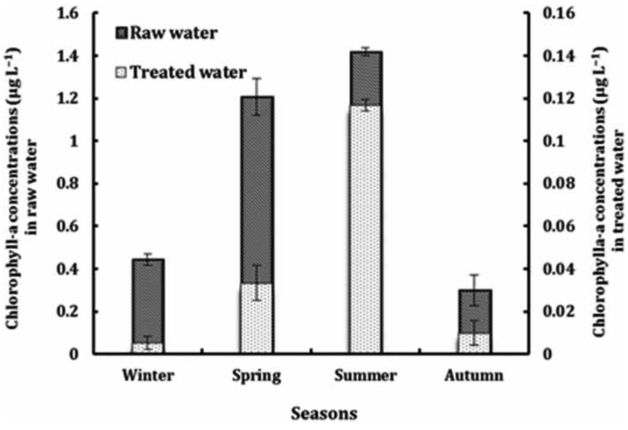

Figure 4 | Phytoplankton chlorophyll-a contents (µg L^{-1}) in raw and treated water of Kafr El-Shinawy drinking-water treatment plant – Damietta. Values are means of three replicates ± SE.

respiration. The slight decrease in pH of treated water (7.34–7.86) below that of raw water (7.76–8.51) was due to the addition of chlorine and alum during treatment processes of raw water.

DO level is an indicator of the water's ability to support a well-balanced aquatic life and acts as an indicator of the trophic status of the water body (Salah & El-Moselhy 2015). The increase in DO of treated water (6.67–7.57 mg L^{-1}) above that of raw water (5.10–6.83 mg L^{-1}) might be due to the physicochemical treatment processes of water such as aeration, coagulation, sedimentation, filtration, and addition of oxidative agents. These treatments increased DO and decreased the turbidity of treated water. A significant negative correlation between DO and water temperatures ($r = -0.502$, $p < 0.05$) was also reported by Shehata & Badr (2010). Low values of DO in raw water during the summer (5.10 ± 0.50 mg L^{-1}) might be attributed to high sewage and agricultural pollution that enhance microbial growth in raw water. The high value of BOD in raw water during summer (3.81 ± 0.32 mg L^{-1}) may be attributed to the respiration activity of phytoplankton and other aquatic biotas which is stimulated by increasing water temperature and relative high wastewater discharges.

Low silica concentrations in raw water (2.23–3.60 mg L^{-1}) might be related to the high growth of diatoms, especially during autumn and winter. But, the increased silica in treated water (2.33–4.00 mg L^{-1}) can be related to water recycling of reactive silica as a result of disruption and hydrolysis of some diatoms through water treatment in the flocculation basin and during other treatment processes (Shehata & Badr 2010). The extremely low levels of ammonia (0.01–0.02 mg L^{-1}) and nitrite (0.01–0.05 mg L^{-1}) in treated water may be attributed to the oxidation of

Table 10 | Seasonally variations in TSI behavior of raw and treated water samples at Kafr El-Shinawy drinking-water treatment plant – Damietta

		Season			
Water source	**Treatment**	**Winter**	**Spring**	**Summer**	**Autumn**
Raw water	TSI	47.82	50.13	50.53	46.72
	Trophic state class	Mesotrophic	Meso-eutrophic	Meso-eutrophic	Mesotrophic
Treated water	TSI	33.19	37.13	40.75	34.73
	Trophic state class	Oligotrophic	Oligotrophic	Mesotrophic	Oligotrophic

ammonia and nitrite in the flocculation basin by chlorine. The overall low levels of inorganic nitrogen (ammonia, nitrite, and nitrate) in treated water might be related to their reaction with the chemical reagents during water treatment in the flocculation basin. The pattern of low nutrient level in treated water than in raw water, with marked seasonal interaction, points to an efficient water treatment regime at the experimental water treatment station.

Some heavy metals are xenobiotics, such as Pb, and Cd; whereas some other heavy metals, including Cu, Zn, and Cr, are essential elements for the human body in small quantities, but turn toxic in high doses. In the present study, the low concentrations of heavy metals (Fe, Mn, Zn, Cu, Cr, Co, Cd, Ni, and Pb) in treated water than in raw water may be related to coagulation and sedimentation processes in treatment basins, in addition to the efficiency of physicochemical water treatment processes including ion exchange and precipitation. The higher levels of all the measured heavy metals, especially Mn, Zn, and Fe in phytoplankton cells than in raw and treated water were due to the bioaccumulation capacity of phytoplankton for heavy metals. This study revealed that the bioaccumulation capacity of phytoplankton depends on metal type and phytoplankton species. Phytoplankton cells contain different functional groups, including amino, thio, carboxylic, and hydroxo that can interact with heavy metals (Pourkhabbaz *et al.* 2018). In the present study, correlations between most of the metals at $p < 0.01$ might be due to the existence of these metals in a similar oxidation state reacting in the same manner. Correlation between heavy metals and pH might be related to the effect of pH levels on the solubility of heavy metals. Some heavy metals (Fe, Zn, Cd, Ni, and Pb) in water were correlated with nutrients due to complex formation between nutrient and metal ions.

Disinfection is a crucial way to protect the human from pathogens. Some disinfectants are reacting with naturally occurring disinfection byproduct precursors to form disinfection byproducts such as THMs compounds. In the present study, high concentrations of THMs in treated waters were related to the production of THMs as byproducts during the chlorination of water (Genisoglu *et al.* 2019). High level of THMs is one of the serious problems for human health in drinking water that can lead to a considerable burden of bladder cancer (Evlampidou *et al.* 2020). A negative correlation of THMs levels with phytoplankton numbers might be due to the reaction of phytoplankton biomass and their extracellular products with chlorine to produce THMs.

In the present study, the microscopic investigation of phytoplankton in water samples revealed that phytoplankton was diverse and can be considered as a bioindicator for water quality. The lower number of total phytoplankton at the output of Kafr El-Shinawy water treatment plant compared with its input is due to the high concentrations of nutrients at the input (meso-eutrophic state of raw water). High growth of Cyanophyta during summer in both raw (91.74%) and treated (77.78%) water are consistent with the findings of Shehata *et al.* (2009) who reported that Cyanophyta had its maximum density in summer. The predominance of Bacillariophyta in raw water during winter (77.93%) is due to the high growth of *M. granulata* ($1{,}931 \times 10^5$ cell L^{-1}), *Nitzschia vermicularis* (631×10^5 cell L^{-1}), *C. meneghiniana* ($1{,}827 \times 10^5$ cell L^{-1}), and *Navicula radiosa* (923×10^5 cell L^{-1}) which correlated with eutrophication and low temperature of water (17.9 ± 2.48 °C). This result was in agreement with Abdel-Hamid & Galal (2019) who concluded that Bacillariophyta growth was favored by the low temperature and was tolerant to the different pollution types. High numbers of Chlorophyta in water during the winter might be attributed to the dominance of various species of *Pediastrum* that flourishes in the winter months (Cho *et al.* 2017). In contrast to the present result, Rajagopal et al. (2010) pointed out that the productivity of Chlorophyta increased at high water temperature. High turbidity of water during summer is responsible for the decrease in Chlorophyta growth as it prevents sufficient light required for Chlorophyta growth. A negative correlation between Bacillariophyta numbers and silica concentration ($r = -0.356$, $P < 0.01$) of water was also reported by Cetin & Sen (1998).

Estimating phytoplankton chlorophyll-a content in water is a direct way of tracking phytoplankton growth and algal blooms (Farouk *et al.* 2020). High phytoplankton chlorophyll-a levels indicate the high nutrient content of water especially nitrogen and phosphorus. Differences in chlorophyll-a concentration during the study period and according to water treatment reflect changes in phytoplankton numbers in raw and treated water. Similar to cell numbers of Cyanophyta, phytoplankton chlorophyll-a concentrations were not completely depleted after various treatment processes. The relative high content of chlorophyll-a in treated water in summer was due to relative high pH (7.86 ± 0.78) and alkalinity (164.7 ± 16.3 mg L^{-1}) values of water as chlorophyll-a degredation decreased and chlorophyll-a stability increased with increasing pH and alkalinity (Gaur *et al.* 2007).

High concentrations of both intracellular and extracellular microcystins in raw and treated water during summer are in agreement with Mohamed *et al.* (2015) that microcystin production increases in accordance with the increase in water temperature and level of nutrients. The existence of higher concentrations of extracellular microcystin in treated water (1.00–2.01 μg L^{-1}) than raw water (0.56–1.30 μg L^{-1}) can be related to the release of the intracellular microcystin in water as a consequence of membrane leakage of cyanobacterial cells through the effect of pre-oxidant compounds such as chlorine dioxide, ozone, copper sulfate, and chlorine on membrane integrity (Pantelic *et al.* 2013). Meanwhile, the high levels of extracellular microcystin in treated water occurred at the expense of intracellular microcystin. There were various microcystin variants produced by *M. aeruginosa*, isolated from the Nile River such as microcystin-LR, microcystin-RR, and microcystin-YR. Moreover, environmental conditions can also indirectly affect microcystin production (Zhang *et al.* 2020).

A great many of the world's drinking-water sources suffer from eutrophication and outbreaks of cyanobacteria, mainly as a result of increased stream regulation. TSI is a number that can be used to classify water in different trophic states. TSI assesses water quality regarding nutrient enrichment and its relationship with excessive growth of algae. Chlorophyll-a and TP are key indicators used to determine the trophic state. It could range from oligotrophic to hypereutrophic. In the present study, TSI values of water samples at input and output of Kafr El-Shinawy treatment plant based on total-P and chlorophyll-a had been estimated and were significantly different. In the present study, the relative higher trophic state of raw water (TSI = 46.72–50.53) than that of treated water (TSI = 33.19–40.75) throughout the year was due to high concentrations of nutrients (total-P, total-N, nitrite, nitrate, and ammonia) in raw water. Nitrogen and phosphorus in raw water are generated from human and industrial wastes. High values of turbidity in raw water especially during spring (6.01 ± 0.57 NTU) and summer (6.00 ± 0.57 NTU) could be attributed to the meso-eutrophic state of water and high phytoplanktonic growth (mainly Cyanophyta). While low values of turbidity in treated water especially during winter (1.27 ± 0.12 NTU) and autumn (1.34 ± 0.13 NTU) could be due to the oligotrophic state of water. Several previous studies reported that the primary production of phytoplankton is an important indicator used in assessing water trophy. It explained the positive correlations of TSI with phytoplankton (Cyanophyta and Chlorophyta) numbers.

CONCLUSIONS

This study presents information on water quality at Kafr El-Shinawy drinking-water treatment plant to provide clean and safe drinking water. The study demonstrated that the phytoplankton composition depends on the changes in physicochemical properties of water as well as the trophic status of water. The optimized physicochemical properties of raw water and meso-eutrophic state increase the phytoplankton growth especially, cyanobacteria to a level of bloom formation. The high growth of cyanobacteria led to the production of cyanotoxins with a high content of intracellular microcystin and low content of extracellular microcystin in raw water. On the contrary, most of the intracellular microcystins were released in treated water during water treatment processes. Phytoplankton cells control the levels of heavy metals in raw and treated water through their bioaccumulation capacity. Consequently, heavy metal levels in raw and treated water are less than those in phytoplankton cells. THMs were higher in treated water than in raw water, with marked efficiency of the physical-chemical treatment of water in the flocculation basin. The dissolved microcystin and THMs contents in treated water are higher than the allowable limit. The present study recommends that ecotechnology or biomanipulation could be used in Kafr El-Shinawy drinking-water treatment plant for improving the water quality and to decrease eutrophication.

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The authors declare that they have no conflict of interest.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animals performed by any of the authors.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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