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RESEARCH ARTICLE

Chasing Light: How Dichromatic LEDs Affect the Elemental Profile of *Gongolaria barbata*

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Abstract: This study aims to investigate the influence of three different dichromatic LED light sources and varying photoperiod durations on the mineral content and trace element compositions in cultivated *Gongolaria barbata* under controlled culture conditions. During the experiment, red-blue (RB), blue-green (BG), red-green (RG) and fluorescent lights were examined at 16:16, 12:12, and 8:16 Light: Dark (L:D) photoperiods, and at 150 µmol photon m^{-2} s^{-1} intensity of light in all treatments. The elemental compositions of the thallus samples were analyzed for Mg, Ca, K, Na, P, Zn, Mo, Cu, Mn, Cr, Co, Cd, Fe, and As.. Our results showed that macro element and trace element compositions significantly varied among different experimental groups. Regarding the order of abundance, macroelements were ranked as follows: K > Na > Ca > Mg > P. Meanwhile, trace elements followed this order: As > Zn > Mn > Cr > Co > Cu > Cd > Mo > Fe. Among the experiment groups, the highest value of the macro elements was recorded as 1041.3±22.2 mg kg^{-1} for K, and the lowest value was 26.61±0.02 mg kg^{-1} for the P. Among the trace elements, for As, the highest value was recorded as 1339.86±5.27 µg kg $^{-1}$, and the lowest was determined at 1.93±0.04 mg kg^{-1} for the Fe. The findings highlight that LED lighting conditions can significantly influence the elemental composition of *G. barbata*.

Anahtar kelimeler:

Makro elementler
İz elementler
Kahverengi deniz yosunu
Gongolaria barbata
Dikromatik LED

Işığın peşinde: Dikromatik LED'ler *Gongolaria barbata*'nın Elementel Profilini Nasıl Etkiler?

Öz: Bu çalışmanın amacı, kontrol koşullarında yetiştirilen *Gongolaria barbata*'nın mineral içeriği ve iz element değişimleri üzerinde üç farklı dikromatik LED ışık ve değişen fotoperiyot sürelerinin etkisini araştırmaktır. Deneme aşamasında, kırmızı-mavi (RB), kırmızı-yeşil (RG), mavi-yeşil (BG) ve floresan (F) LEDler, sırasıyla 16:16, 12:12 ve 8:16 Aydınlık:Karanlık (L:D) fotoperiyotlarında, her biri 150 µmol photon m^{-2} s^{-1} yoğunluğunda incelenmiştir. Tallusların; Ca, K, Mg, Na, P, Zn, Mo, Mn, Fe, Cu, Cr, Co, Cd ve As kompozisyonları analiz edilmiştir. Sonuçlarımıza göre, makroelement ve iz element kompozisyonları farklı deney grupları arasında önemli varyasyonlar gösterdi. Türde bulunan makroelementlerin sıralaması şu şekildedir: K > Na > Ca > Mg > P, aynı zamanda iz elementler şu sırayı takip etmektedir: As > Zn > Mn > Cr > Co > Cu > Cd > Mo > Fe. Deneme grupları arasında, makro elementlerin en yüksek değeri K elementi için 1041.3±22.2 mg kg^{-1} olarak belirlenirken, en düşük değer P için 26.607±0.02 mg kg^{-1} olarak belirlendi. İz elementler arasında ise en yüksek değer As için 1339.86±5.27 µg kg^{-1} tespit edilirken, en düşük değer Fe için 1.930±0.04 mg kg^{-1} olarak belirlendi. Bulgular, LED aydınlatma koşullarının *G. barbata* türünün elementel kompozisyonunu önemli ölçüde etkileyebileceğini vurgulamaktadır.

Introduction

Macroalgae, commonly known as seaweeds, are considered as multifaceted marine resources with diverse ecological, nutritional, and industrial significance (Lourenço-Lopes et al., 2020). These photosynthetic organisms are pivotal contributors to global oxygen production and hold immense potential as sustainable sources of essential minerals, bioactive compounds, and functional ingredients for human consumption (Fleurence, 1999). Moreover, macroalgae possess a rich nutritional profile and bioactive compounds with potential antioxidant, anti-inflammatory, and anti-diabetic properties, positioning them as a potential functional food source (Rodrigues et al., 2015).

These sessile organisms adapt to the ever-changing underwater light environment, influencing their physiological responses, pigmentation, and growth patterns (Figueroa et al., 2014). Environmental factors such as solar radiation, water column depth, and dissolved organic matter

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influence light conditions underwater, leading to variations in the composition and growth of macroalgal communities (Lüning, 1991). Light conditions play a pivotal role in shaping mineral accumulation dynamics of macroalgae, a diverse group of marine organisms with substantial promise for addressing nutritional deficiencies and enhancing human health. The nuanced interplay of light spectra, notably the red: far- red and blue: red ratios, is recognized for its role in signaling diurnal and annual photoperiods, thereby influencing the growth cycles of macroalgae (Figueroa et al., 1995)

Indoor algal aquaculture has been transformed by the use of light-emitting diodes (LEDs), surpassing conventional lighting approaches. It is a fundamental driver of photosynthesis, metabolism, and overall growth in conventional fluorescent lamps regarding economic efficiency and technological advancement (Schulze et al., 2014). LEDs offer a host of advantages, including the ability to finely tune light intensity to simulate natural sunlight fluctuations throughout the day, the capacity to generate high light levels with minimal heat emission, and the extended lifespan, typically 20–30 nm at half-peak height in their narrow emission spectrum, enabling precise control for studies in photomorphogenesis and other plant responses to light (Choi et al., 2015; Yeh and Chung, 2009). In their study, Öztaşkent and Ak, (2021) evaluated the effects of LED lights on the pigment, growth, and biochemical composition of *Treptecanta barbata* (formerly known as *Cystoseira barbata*). Red LED light sources were observed to have a significant impact on the specific growth rate of *T. barbata*, leading to a remarkable 61% increase compared to the control group. Notably, it was found that red LED light specifically elevated the protein content in this brown seaweed. Light and salinity effects on the mineral levels of *T. barbata* were also examined by Ak et al., (2022). The elemental values of these brown algae from wild stocks were compared with those of cultured thallus. In the culture experiments, 11 trials with light intensity ranging from 50 to 150 μmol photons m^{-2} s^{-1} and salinity ranging from 24 to 42 ppt were designed using response surface methodology (RSM). According to the results, light intensity and salinity changes were modeled for element accumulation in *T. barbata*. Most of the elements were influenced by salinity rather than light intensity. Okumura et al., (2014) have harnessed these features by developing LED array systems tailored to specific algal growth requirements, demonstrating notable enhancements in growth efficiency and cost-effectiveness.

In the study by Kim et al., (2015), it was observed that the use of mixed-color LED lighting, as opposed to cool white fluorescent lighting, resulted in higher concentrations of chlorophyll and carotenoids during the cultivation of *Gracilaria tikvahiae*. The mineral content within macroalgae has garnered considerable attention due to its potential to provide essential nutrients and trace elements crucial for various physiological processes (Rodrigues et al., 2015; Afonso et al., 2018). Macroalgae can accumulate calcium, magnesium, potassium, iron, and iodine minerals essential for human well-being (Circuncisão et al., 2018).

Understanding the intricate relationship between light conditions and mineral composition within macroalgae is pivotal for comprehending their physiological responses. Among the extensive array of macroalgal species, those belonging to the genus *Gongolaria*, a representative of the brown algae group, play a critical ecological role as "ecosystem engineers" in temperate rocky reefs (Thibaut et al., 2016). Macroalgae, including *Gongolaria* species, have drawn attention as promising candidates for addressing dietary mineral deficiencies and enhancing the nutritional value of human diets. These marine organisms have demonstrated a unique capacity to accumulate and concentrate minerals from their surrounding aquatic environments (Holdt and Kraan, 2011).

While there have been studies on the effects of monochromatic LED lights and salinity on the elemental composition of *Gongolaria barbata* (Stackhouse) Kuntze, 1891, there is currently no research available regarding how different types and intensities of dichromatic LED lights impact the chemical content of this species.

The aim of this study is to investigate the effects of three different dichromatic LED light sources and varying photoperiod durations on the mineral content and trace element fluctuations in *G. barbata* cultivated under controlled conditions. During the experimental phase, red-blue, red-green, green-blue, and fluorescent lights were examined at 16:16, 12:12, and 8:16 Light: Dark (L:D) photoperiods, each with 150 μmol photons $m^{-2}s^{-1}$ intensity of light. The elemental compositions of the thallus samples, including Ca, Mg, P, Na, K, Zn, Mo, Mn, Cu, Fe, Cr, Co, As and Cd were analyzed. These investigations aim to provide valuable insights into optimizing artificial lighting systems for closed macroalgae production environments, facilitating sustainable seaweed cultivation for diverse industrial and ecological applications.

Material and Methods

Macroalgae media and cultivation

In this study, *G. barbata* thallus were obtained from established stock cultures and were cultivated in specialized 50 l Plexiglas tanks. These tanks were filled with UV-sterilized seawater and maintained at temperature of 24 °C. The tanks were illuminated with an irradiance level of 150 μmol photon m^{-2} s^{-1}, which was monitored using an LI-250 light meter from Li-Cor (USA). Throughout the acclimatization period, the cultures were exposed to continuous illumination for 24 hours daily to prevent shading among thallus and ensure consistent light exposure. For the experiments, healthy thalli were carefully selected and placed into glass bottles. The experiments were carried out for five weeks. Three color combinations of LED lights (blue-red, green-red, and blue-green) and three photoperiods (16:8, 12:12, 8:16 (L:D)) were employed for experimentation, while the control group was subjected to the daylight fluorescent light (Table 1). The positioning of the LED lights was arranged symmetrically in the culture chambers.

To conduct the experimental trials, 3 l cylindrical glass bottles, each with a diameter of 15 cm, were employed. The stock density for these trials was established at 5 g l^{-1}, maintaining consistency across the experiment and facilitating accurate observations and measurements. The bottles were aerated by introducing air bubbles, creating a conducive environment for the thalli. The choice of growth medium was crucial for the experimental setup, and the Conway medium was employed consistently throughout the experiments (Tompkins et al., 1995). The pH values were diligently measured and recorded throughout the experiments. These measurements were conducted utilizing a pH meter manufactured by Hanna Instruments (model HI8314). Other culture parameters of culture like salinity and temperature maintained according to the specifications detailed by (Ak et al., 2022). Specifically, the salinity level was maintained at a constant 36‰, while the temperature was regulated to remain within the range of 24 ± 1 °C.

Element analysis

For element analysis, the samples were subjected to examination using the Varian Liberty AX Sequential ICP-AES instrument, employing the Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) technique. This analysis encompassed a wide range of elements, including silver (Ag), potassium (K), arsenic (As), aluminum (Al), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), calcium (Ca), phosphorus (P), and zinc (Zn), as outlined by the Nordisk Metodikkomité for Næringsmidler (2007). To ensure accuracy and prevent secondary contamination, procedures recommended by the Marine Strategy Framework's 8th and 9th task groups were rigorously followed (Law et al., 2010). All analyses were performed in triplicate, and each set of measurements was carried out in three replicates to account for variability and ensure robustness. The measured values were reported as parts per million (ppm) and per billion (ppb), quantitatively representing the elemental concentrations within the samples.

Data evaluation

To evaluate variances in elemental compositions among the different trials, a one-way analysis of variance (ANOVA) was conducted.

Table 1. Experiment group design

Photoperiod (L:D)	LED Condition	Code
16:8	Fluorescent	16:8 F
	RB (Red LED %50 + Blue LED %50)	16:8 RB
	RG (Red LED %50 + Green LED %50)	16:8 RG
	GB (Green LED %50 + Blue LED %50)	16:8 GB
12:12	Fluorescent	12:12 F
	RB (Red LED %50 + Blue LED %50)	12:12 RB
	RG (Red LED %50 + Green LED %50)	12:12 RG
	GB (Green LED %50 + Blue LED %50)	12:12 GB
8:16	Fluorescent	8:16 F
	RB (Red LED %50 + Blue LED %50)	8:16 RB
	RG (Red LED %50 + Green LED %50)	8:16 RG
	GB (Green LED %50 + Blue LED %50)	8:16 GB

Results and Discussion

In our study, we aimed to investigate how photoperiods (16:8, 12:12, and 8:16 L:D) and dichromatic light colors (F, RB, RG, and BG) impact the cultivation of *G. barbata*. The macro and trace elements of the *G. barbata* samples, cultivated under various LED photoperiod conditions, are given in Table 2. Among the experiment groups, the highest value of the macro elements was recorded as 1041.3±22.2 mg kg^{-1} dry weight (dw) for the element K, and the lowest value was determined as 26.61±0.02 mg kg^{-1} dw for the P element. For trace elements, the highest value was determined for the As 1339.86±5.27 µg kg^{-1} dw, and the lowest was determined at 1.93±0.04 mg kg^{-1} dw for the Fe. According to our results, the highest Ca value was recorded in the 16:8 photoperiod control group, at 186.45±0.37 mg kg^{-1}. Generally, the lowest values were recorded in the 12:12 photoperiod, with the lowest being 87.17±19.00 mg kg^{-1} dw in the RG group. The highest Mg value was recorded in the 16:8 F, with values in the 8:16 groups being the lowest. The macro elements identified in the species were ranked in the following order from highest to lowest concentration: K > Na > Ca > Mg > P. For the trace elements found in the species, they were arranged in the following order from highest to lowest concentration: As > Zn > Mn > Cr > Co > Cu > Cd > Mo > Fe.

Macro elements

Our research findings indicated that, based on elemental data, the highest Na values were recorded in the 12:12 photoperiod group with 564.68±10.18 mg kg^{-1}, while the lowest value recorded in the 8:16 photoperiod, 311.23±0.99 mg kg^{-1} (Table 2). In the study by Aşıkkutlu and Okudan (2021), the sodium (Na) content was determined to be 6.46 mg g^{-1} in *Cystoseira foeniculacea* and 8.36 mg g^{-1} in *Gongolaria montagnei*. Meanwhile, Kravtsova et al. (2014) reported the highest recorded Na values for *C. barbata*, ranging from 11.3 mg g^{-1} to 26.60 mg g^{-1}, and the highest average Na values for *C. crinita* species were in the range of 20.00 mg g^{-1} to 25.30 mg g^{-1}. Upon comparing our study's data with previous studies, it is evident that the sodium content values in our study were lower than those reported in the earlier research. The highest value was recorded for K in the 12:12 (L:D) photoperiod control group (1041.3±22.2 mg kg^{-1}), while the lowest was measured at 559.33±1.56 mg kg^{-1} in the 8:16 (L:D) photoperiod RB group. K was found to be 28.97 mg g^{-1} in *C. foeniculacea* species and 22.71 mg g^{-1} in *G. montagnei* species, according to the study Aşıkkutlu and Okudan (2021). Our study's values are lower than those of previous studies.

Our study found Mg values higher at 16:8 F, 139.05±1.48 mg kg^{-1} and lowest at 8:16 (L:D) BG, 91.89±0.72 mg kg^{-1} (Table 2). Manev et al. (2021) found a Mg composition of 6.60 mg kg^{-1}, and Szelag-Sikora et al. (2016) found the highest mean in the *Cystoseira barbata* species as 6.26 mg g^{-1} and the lowest value of 4.70 mg g^{-1}. Also, Aşıkkutlu and Okudan (2021) found Mg as 0.63 mg g^{-1} in *C. foeniculacea* and 0.62 mg g^{-1} in *G. montagnei*. According to previous studies our results are higher than those reported in the study of Manev et al. (2021) and lower than those reported by Aşıkkutlu and Okudan (2021) and Szelag-Sikora et al. (2016).

For Ca, our highest value for *G. barbata* was 186.45±04 mg kg^{-1}, 16:8 F (L:D), and the lowest was 105,06±0,25 mg kg^{-1} at 12:12 BG (L: D) (Table 2). According to Aşıkkutlu and Okudan, (2021), Ca was determined as 7.84 mg g^{-1} in *C. foeniculacea* and 11.23 mg g^{-1} in *G. montagnei*. Manev et al., (2013) found the Ca composition of *C. barbata* from Cape Rusalka near the Black Sea at 41.60 mg kg^{-1}. Szelag-Sikora et al. (2016) found the highest mean value for Ca in the *C. barbata* as 24.83 mg g^{-1}, and the lowest was 9.03 mg g^{-1}. We observed that our study's values were lower when compared to previous studies.

Our study detected a P range between 78.77±0.25 mg kg^{-1} (8:16 RB (L:D)) to 28.60±0.02 mg kg^{-1} (12:12 RG (L:D) (Table 2)). In previous studies, P values were recorded as 316.84 mg kg^{-1} in *C. foeniculacea* and 370.35 mg kg^{-1} in *G. montagnei* (Aşıkkutlu and Okudan, 2021). Szelag-Sikora et al. (2016) found ranges between 1.24 mg g^{-1} to 0.47 mg g^{-1} in *C. barbata*. According to previous studies our results were lower than Aşıkkutlu and Okudan (2021) and Szelag-Sikora et al. (2016).

Na/K ratio was detected as the highest 0.68±0.01 mg kg^{-1} in our study. Low Na/K ratios characterize macroalgae. This ratio is considerably lower than those found in various foods, such as olives (43.6), cheddar cheese (8.7) and sausages (4.9). Previous research data indicate that green algae have Na/K ratios ranging from 0.9 to 1 mg kg^{-1}, red algae from 0.1 to 1.8 mg kg^{-1}, and brown algae from 0.3 to 1.5 mg kg^{-1}. The World Health Organization (WHO) recommends Na/K ratios close to unity, highlighting the importance of evaluating the consumption of foods with this ratio or lower for healthy cardiovascular purposes. However, it is worth noting that many developing and developed countries currently have an average daily Na intake of 3.95 mg/day, nearly double the recommended daily intake, which could lead to a general increase in Na intake without considering alternative dietary sources. Using seaweeds like *Cystoseira* in processed foods instead of NaCl (table salt) could be an excellent strategy to reduce overall sodium consumption while increasing potassium intake and enhancing the intake of other essential elements not typically found in the diet.

Trace elements

In Table 3, previous studies for trace elements are given. Macroalgae can accumulate and concentrate elements from their surrounding aquatic environments (Holdt and Kraan, 2011). Seaweeds can serve as a source of trace elements essential for maintaining health, including Fe, Mn, Cu, Zn, and Co. These organisms can accumulate elements necessary for sustaining human health, including Ca, Mg, P, and Fe. Furthermore, macroalgae possess a rich nutrient profile and harbor potential bioactive compounds with antioxidant, anti-inflammatory, and anti-diabetic properties, positioning them as a potential functional food source (Rodrigues et al., 2015; Afonso et al., 2019).

Looking at trace element data, for Zn, the highest value was recorded in the 16:8 F group with 908.06±1.0 µg kg^{-1} while the lowest value was found in the 8:16 RB group at 300.25±0.78 µg kg^{-1}. Different researchers have documented considerable fluctuations in Zn concentrations, even when studying identical macroalgae species. For instance, Akçalı and Küçükksezgin (2011) found Zn content in *Cystoseira sp.* 75.5 ± 12.3 µg g^{-1} collected from Çanakkale/City and 36.9 ± 2.04 µg g^{-1} Çanakkale/Dardanos. Aşıkkutlu and Okudan (2021) found 3.32 mg kg^{-1} in *C. foeniculacea* and 6.87 mg kg^{-1} in *G. montagnei*.

With respect to Fe, the highest value was measured in the 12:12 F group as 5.96±0.03 mg kg^{-1}, while the lowest value was recorded in the 8:16 BG group as 1,93±0,04 mg kg^{-1}. The mean iron concentrations of *Cystoseira sp*. were reported as 302.3 ± 16.6 mg kg^{-1} in the Çanakkale/city center region and 186.6 ± 19.4 mg kg^{-1} in the Çanakkale/Dardanos region (Akçalı and Küçükksezgin, 2011). In the study conducted by Arıcı et al. (2019), the average Fe concentration in *Cystoseira crinita* was reported as 322.5 mg kg^{-1}. In the research conducted by Aşıkkutlu and Okudan (2021), the Fe content was determined as 0.29 mg g^{-1} in *Cystoseira foeniculacea* and 0.67 mg g^{-1} in *Gongolaria montagnei*.

Table 2. Elemental Composition of *G. Barbara* cultivated under different LEDs and photoperiods (DW)

		Ca (mg kg^{-1})	**K** (mg kg^{-1})	**Mg** (mg kg^{-1})	**Na** (mg kg^{-1})	**P** (mg kg^{-1})	**Na/K** (mg kg^{-1})	**Fe** (mg kg^{-1})	**Mo** (µg kg $^{-1}$)
16:8	F	186,45±0,37^{a}	809,55±1,08^{c}	139,05±1,48^{a}	297,57±0,46^{d}	31,91±0,15^{d}	0,37±0,01^{d}	3,21±0,017^{c}	5,54±0,22^{a}
	RB	128,15±2,57^{b}	845,36±13,6^{b}	116,10±0,05^{c}	387,20±5,65^{b}	35,35±0,01^{b}	0,46±0,011^{a}	3,33±0,01^{b}	5,55±1,04^{a}
	RG	113,25±0,61^{c}	738,65±3,60^{d}	126,12±0,39^{b}	330,71±2,46^{c}	33,11±0,01^{c}	0,45±0,01^{b}	4,54±0,02^{a}	6,09±0,6^{a}
	BG	105,06±0,25^{d}	1030,10±5,9^{a}	129,10±2,16^{b}	423,71±3,12^{a}	36,71±0,08^{a}	0,41±0,01^{c}	2,56±0,02^{d}	6,56±0,62^{a}
12:12	F	101,47±1,92^{b}	934,44±15,6^{b}	124,35±0,19^{b}	475,41±7,98^{b}	32,04±0,08^{b}	0,51±0,01^{d}	3,89±0,002^{c}	7,96±0,08^{a}
	RB	115,76±1,59^{a}	1041,3±22,2^{a}	134,25±1,77^{a}	564,68±10,2^{a}	39,49±0,12^{a}	0,54±0,01^{b}	5,96±0,03^{a}	7,92±0,43^{a}
	RG	87,17±1,96^{c}	859,3±18,8^{c}	123,353±1,2^{b}	446,4±10,06^{c}	28,61±0,02^{c}	0,52±0,01^{c}	2,65±0,02^{d}	6,01±0,31^{b}
	BG	116,97±2,47^{a}	791,6±13,92^{d}	110,03±0,01^{c}	541,31±9,32^{a}	28,82±0,07^{c}	0,684±0,01^{a}	5,48±0,013^{b}	8,37±0,45^{a}
8:16	F	106,18±0,58^{b}	614,43±8,11^{c}	98,47±0,56^{a}	336,04±3,67^{b}	46,95±0,55^{d}	0,55±0,01^{b}	2,99±0,01^{a}	6,40±1,135^{a}
	RB	110,36±0,24^{b}	559,33±1,57^{d}	94,53±0,97^{b}	311,23±0,99^{c}	78,77±0,25^{a}	0,56±0,02^{a}	2,29±0,013^{b}	6,16±1,07^{a}
	RG	120,03±3,23^{a}	640,839±0,9^{b}	94,963±0,6^{b}	313,36±1,08^{c}	72,05±0,07^{b}	0,49±0,01^{d}	2,15±0,01^{c}	6,04±0,56^{a}
	BG	107,57±2,21^{b}	687,01±3,90^{a}	91,89±0,72^{c}	351,08±1,81^{a}	64,45±0,29^{c}	0,51±0,01^{c}	1,93±0,04^{d}	6,98±0,45^{a}

*Different lowercase letters show the significant differences between the groups according to the ANOVA results ($p<0.05$)

Table 2. Continued

		Mn (μg kg $^{-1}$)	Zn (μg kg $^{-1}$)	Cu (μg kg $^{-1}$)	Cr (μg kg $^{-1}$)	Co (μg kg $^{-1}$)	Cd (μg kg $^{-1}$)	As (μg kg $^{-1}$)
16:8	F	140,15±0,78^{b}	908,06±1,00^{a}	62,1±33,2^{b}	49,80±0,47^{a}	8,48±0,09^{b}	8,89±0,34^{a}	861,86±5,61^{c}
	RB	116,03±1,36^{d}	503,31±1,51^{d}	52,1±28,8^{cd}	51,69±0,86^{a}	9,57±0,46^{a}	4,01±0,09^{b}	828,43±2,47^{d}
	RG	147,51±1,19^{a}	734,81±1,98^{c}	52,7±28,8^{c}	49,91±1,12^{a}	9,96±0,14^{a}	4,229±0,325^{b}	900,6±12,71^{b}
	BG	120,30±0,83^{c}	766,99±0,75^{b}	74,1±30,5^{a}	43,94±1,07^{b}	8,38±0,66^{b}	4,160±0,21^{b}	1329,86±5,3^{a}
12:12	F	180,68±0,43^{c}	551,54±3,14^{b}	53,8±26,6^{a}	65,38±0,00^{cA}	86,579±0,28^{b}	3,183±0,19^{b}	1199,52±3,4^{b}
	RB	227,04±1,68^{a}	657,29±4,20^{a}	61,1±33,0^{a}	114,85±1,91^{a}	88,14±0,67^{a}	4,2980±0,02^{a}	1339,19±2,4^{a}
	RG	120,79±0,05^{d}	547,82±2,89^{b}	54,0±29,0^{a}	48,56±0,72^{d}	70,61±0,36^{d}	4,76±0,05^{a}	842,25±1,12^{d}
	BG	223,81±0,69^{b}	528,98±3,11^{c}	52,2±28,8^{a}	96,453±0,47^{b}	81,56±0,68^{c}	2,68±0,35^{b}	1161,1±7,04^{c}
8:16	F	159,04±0,83^{a}	370,75±2,08^{b}	68,5±43,6^{a}	55,83±0,49^{a}	10,48±0,31^{d}	5,12±0,42^{a}	459,33±5,81^{b}
	RB	119,02±1,53^{b}	300,25±0,78^{d}	55,0±33,8^{a}	51,56±0,38^{b}	11,96±0,07^{c}	2,71±0,37^{bc}	366,62±6,08^{d}
	RG	120,91±2,54^{b}	511,38±9,05^{a}	73,9±44,3^{a}	45,417±0,6^{d}	86,28±0,57^{a}	3,07±0,06^{b}	482,76±0,48^{a}
	BG	107,74±0,10^{c}	337,64±2,13^{c}	62,7±37,2^{a}	48,55±0,58^{c}	22,47±0,54^{b}	2,25±0,14^{c}	2,22±0,011^{d}

* Different lowercase letters show the significant differences between the groups according to the ANOVA results ($p<0.05$)

Table 3. Previous studies on trace elements in *Cystoseira* and *Gongolaria* species (mg kg^{-1})

Region/ Site	**Species**	**As** mg kg^{-1}	**Cd*** µg kg^{-1}	**Cu** mg kg^{-1}	**Cr** mg kg^{-1}	**Zn** mg kg^{-1}	**Co** mg kg^{-1}	**Fe** mg kg^{-1}	**References**
Çanakkale	*Cystoseira sp.*	-	89.9± 9.18	6.73± 1.72	2.13± 0.71	75.5± 12.3	6.24± 1.04	302.3± 16.6	Akçalı and Küçükksezgin, (2011)
Dardanos	*Cystoseira sp.*	-	278.3±49.2	3.13± 0.36	4.76± 0.80	36.9± 2.04	2.31± 0.39	186.6± 19.4	Akçalı and Küçükksezgin, (2011)
Sinop	*C.crinita*	0.87	-			47.89	19.09	322.5	Arıcı et al., (2019)
Black Sea	*C. barbata*	-	-	5-37	-	65		327±18	Arici and Bat, (2016)
Greece	*C. barbata*	-	60- 2600	0.7- 8.8	-	8.8- 58.1	0.02- 2.5	-	Sawidis et al., (2001)
Bulgaria	*C.crinita*	0.85	-	-	0.04	1.63	0.02	6.1	Kravtsova et al., (2014)
Crimea	*C. crinita*	28.1	-	-	-	18.6	19.09	1460	Kravtsova et al., (2014)
Antalya	*C. foeniculacea*	-	800± 300	1.66± 0.46	1.00±0.01	3.32± 0.49	1.00± 0.01	289.88±48.96	Aşıkkutlu and Okudan, (2021)
Antalya	*G.montagnei*	-	-	6.22± 0.63	1.64± 0.47	6.87± 0.88	0.98±0.01	667.72±162.21	Aşıkkutlu and Okudan, (2021)

The highest value for Cd was observed in the 16:8 F group as 8.89±0.34 µg kg^{-1}, with the lowest value being determined in the 8:16 RB group as 2.25±0.14 µg kg^{-1}. Reported Cd concentrations in various species of seaweeds are given in Table 3. In the study by Aşıkkutlu and Okudan (2021), it was found that Cd levels were 0.80 mg kg^{-1} in *Cystoseira foeniculacea*. In *Cystoseira crinita,* the mean Cd concentration was 0.23 mg kg^{-1} (Arıcı et al., 2019). Akcalı and Küçüksezgin (2011) conducted a study on *Cystoseira sp*. and reported the mean Cd concentrations as 0.09 mg kg^{-1} in Çanakkale/city center and 0.05 mg kg^{-1} in Çanakkale/Dardanos. Our results on Cd were lower than those reported in previous studies.

For Mn, the highest value was measured at 227.04±1.68 µg kg^{-1}, and the lowest was 107.74±0.11 µg kg^{-1}. Aşıkkutlu and Okudan (2021), reported a Mn level of 0.79 mg kg^{-1} in *G. montagnei*, while it was below the measurement range in *C. foeniculace*. Ak et al., (2020) found that the mean Mn concentration in *C. barbata* was 0.18 mg kg^{-1}. Our results showed lower Mn levels than those reported in the existing literature.

In the present study, the highest value for Cu was measured as 74.1±30.5 µg kg^{-1} at 16:8 BG and the lowest as 52.1±28.8 µg kg^{-1} at 16:8 RG. Aşıkkutlu and Okudan (2021), observed that Cu levels were 1.66 mg kg^{-1} in *C. foeniculacea* and 6.22 mg kg^{-1} in *G. montagnei*. A mean Cu concentration of 10.20 mg kg^{-1} in *C. barbata* and 4.27 mg kg^{-1} in *Cystoseira crinite* were reported by Arıcı et al., (2019). In the study by Akçalı and Küçüksezgin (2011) on *Cystoseira sp*., the mean Cu values were determined as 6.73 mg kg^{-1} in the Çanakkale/city center and 3.13 mg kg^{-1} in the Çanakkale/Dardanos. Our results were considerably lower than those reported in earlier studies.

In this study, the highest Co value was 88.143±0.67 µg kg^{-1} at 12:12 RB, and the lowest was measured as 8,38±0,66 µg kg^{-1} at 16:8 BG. Co is required for the synthesis of vitamin B12, and is essential for propionate metabolism and cytosolic transmethylation of homocysteine. In an earlier study, Co was reported as 1.00 mg kg^{-1} in *C. foeniculacea* and 0.98 mg kg^{-1} in *G. montagnei* (Aşıkkutlu and Okudan, 2021). Arıcı et al. (2019) measured the mean value for Co in *C. barbata*as 0.50 mg kg^{-1} and in *C. crinita* as 0.57 mg kg^{-1}. Our findings were similar to those reported in other studies.

For Cr, the highest value was measured as 114.85±1.91 µg kg^{-1} at 12:12 RB group and the lowest at 16:8 BG as 43.94±1.06 µg kg^{-1}. The mean Cr values for *Cystoseira sp.* were determined as 2.13 mg kg^{-1} in the Çanakkale/city center region and 4.76 mg kg^{-1} in the Çanakkale/Dardanos region (Akçalı and Küçükksezgin, 2011). In a previous study, Cr was found as 1.00 mg kg^{-1} in *Cystoseira foeniculacea* and 1.64 mg kg^{-1} in *Gongolaria montagnei* (Aşıkkutlu and Okudan, 2021). Overall, our results were lower than those reported in the literature.

In the present syudy, the highest value for As was 1339.19±2.35 µg kg^{-1} and the lowest value was 2.22±0.01 µg kg^{-1}. Arıcı et al. (2019) reported 0.87 mg kg$^{-1,}$ and Kravtsova et al. (2015) reported 28.1 mg kg^{-1}.

Table 4. International regulations on trace element permissible limits in macroalgae (µg g^{-1})

Organization/Authority	As	Cd	Zn	Cu	Fe	References
Ceva, 2014	3	0.5				CEVA, (2014)
Australian and New Zealand Food Standard Authority		1	14	10	8	ANZFA, (2005)
Eu Commission(EC No: 488/2014		3				EC (2008, 2017)
Codex Alimentarius Commission (FAO/WHO)		0.2				FAO/WHO, (1995)
Institute of Medicine USA	10					Institute of Medicine (US), (2001)
Max values in the present study	1.33	0.008	0.9	0.07	5.95	

Daily intake of seaweeds

Even though macroalgae are gaining increased attention as a potential food source, their limited consumption in Europe has led to relatively limited regulations and a lack of consistent EU-level guidelines for macroalgae-based foods. Nevertheless, there are established regulatory limits for the toxic metals and trace elements in macroalgae, which are outlined in Table 4. These results can be cross-referenced with the maximum residual limits (MRLs) set by different authorities. According to EC regulations from 2014 and the Codex Alimentarius Commission (FAO/WHO) (as shown in Table 4), the MRL for Cadmium (Cd) is set at 3 µg g^{-1} and 0.2 µg g$^{-1,}$ respectively, for dried seaweed. Our study indicated that all the experiment groups of *G. barbata* had lower Cd levels than indicated by EC regulation and (FAO/WHO). With respect to Cu, Zn, Fe, and Cd, the Australian and New Zealand Food Standard Authority (ANZFA) regulations specify MRLs of 10 µg g^{-1},14 µg g^{-1}, 2 µg g^{-1}, and 1 µg g^{-1}, respectively (ANZFA, 2005). All the experimental groups in the study had Cu, Zn, Fe, and Cd levels below these MRLs. It is important to note that elevated levels of heavy metals in seagrasses could potentially impact their reproduction, physiology, growth rate, and metabolism as documented in previous studies (Farias et al., 2017; Roberts et al., 2008). Therefore, additional research is necessary to gain a comprehensive understanding of the impact of heavy metals on seagrasses and their ecosystems. Research should focus on to the mechanisms of metal accumulation and the potential for biomagnification within the food chain. Today, macroalgae are recognized as a rich source of diverse bioactive compounds with considerable market potential, highlighted by Holdt and Kraan (2011). One of the fastest-growing segments in the European macroalgae market is the "superfood" category, and macroalgae-based dietary supplements are becoming increasingly common in groceries. However, it is worth noting that the European market is still predominantly supplied by imported macroalgae products (FAO, 2019).

Conclusion

This study investigated the impact of various types of dichromatic LED lights and different photoperiod durations on the macro and trace element compositions of *G. barbata*. The findings highlight that LED lighting conditions can significantly influence the elemental composition of this seaweed species.

Specifically, different LED lighting periods and colors indicated pronounced macro and trace element variations. This variability suggests that *G. barbata* may have distinct nutritional requirements and potential applications based on specific lighting conditions. Furthermore, the ability of macroalgae to accumulate essential elements underscores their potential as a functional food source. This research emphasized the importance of understanding how dichromatic LED lighting conditions could affect the elemental composition of organisms like *G. barbata*, and their potential for sustainable production and diverse industrial applications.

In conclusion, this study contributes to understanding the seaweed's potential for future food and industrial applications by demonstrating how different LED lighting conditions impact the elemental composition of *G. barbata*.

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Conflict of Interest

There is no conflict of interest between the authors.

Author Contributions

MY, and IA contributed the concepts and design of experiments. MY and IA. have performed the experiments MY was carried out data analysis. IA has responsibility for the integrity of the work and the correspondence.

Ethics Approval

Ethics committee approval is not required for this study

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