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Article

Optimization of Irrigation Periods and Magnesium Chlorophyllin Application for Increasing Water Use Efficiency and Productivity of *Mentha longifolia* in South Sinai

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Abstract: A two-season field experiment (2021/2022 and 2022/2023) was conducted on a private farm in the Al-Tour region, South Sinai, Egypt, to evaluate the effects of different irrigation periods and foliar application of magnesium chlorophyllin (Mg-Chl) as well as their interaction treatments on the productivity, water consumption, and water use efficiency of *Mentha longifolia* grown under a drip irrigation system. The experimental design included three irrigation periods (2, 4, and 6 days) and three concentrations of Mg-Chl foliar spray (0, 0.5, and 1 g/L). The results demonstrated that the treatment combining a 4-day irrigation period with 1 g/L Mg-Chl foliar application significantly improved herb fresh yield, herb dry yield, and oil yield per feddan, as well as water use efficiency. This treatment reduced water consumption by 41.42% and increased productivity by 70.7%, indicating a substantial enhancement in water use efficiency. The average crop coefficient (Kc) for *Mentha longifolia* under the conditions of the Al-Tour region were 0.95, 0.92, and 0.96 during the initial, development, and maturity growth stages, respectively. Also, the findings demonstrated that the primary chemical constituents of the extracted essential oils were pulegone, 1,8-cineole, menthone, endo-borneol, à-terpineol, and α-pinene.

Key words: WUE, *Mentha longifolia*, irrigation periods, Kc, Magnesium chlorophyllin.

1. Introduction

Given the strong connection between climate change, water, and food security, and its impact on agricultural production, rising temperatures and decreasing precipitation are expected, which raises concerns, especially in drought-prone and water-scarce regions like

Egypt. Therefore, it is crucial to explore optimal water management methods, improve the efficiency of land and water use, and focus on non-traditional crops that are stress-tolerant and offer high economic returns. Additionally, modern agricultural technologies should be prioritized.

Mentha longifolia L., a member of the *Lamiaceae* family, is widely distributed across Iran, the Mediterranean, Europe, Australia, and North Africa **(Harley and Brighton, 1977)**. In traditional medicine, all parts of the plant leaves, flowers, stems, and seeds have been extensively used for their antibacterial, carminative, diuretic, antitussive, mucolytic, and antispasmodic properties. It has been employed to treat a variety of conditions, including skin diseases, headaches, digestive issues, gout, amenorrhea, colds, and frequent urination (**Naghibi *et al.*, 2010; Gruenwald *et al.*, 2000)**. *Mentha longifolia*'s volatile oil contains terpenoids such as pulegone, isopiperiten-1, and 1,8-cineole (**Sharopov *et al.*, 2012**). The appealing scent and flavor produced by aromatic compounds motivate manufacturers to incorporate additional ingredients, particularly essential oils, into beverages and food products.

Water is a crucial factor influencing plant growth and yield. Efficient use of water resources is becoming increasingly important due to growing competition among domestic, industrial, and agricultural sectors. Agriculture faces significant challenges from high temperatures, drought, salinity, and chemical toxicity in many regions of the world (**Wang *et al.*, 2004; Berenguer *et al.*, 2009**). The need to conserve water resources is especially critical in arid and semi-arid climates, where the threat of climate change exacerbates water scarcity. Drip irrigation systems are effective in maintaining optimal soil moisture levels to maximize crop returns. This high-frequency water management method minimizes the soil's role as a water reservoir, delivering daily water requirements directly to a portion of the plant's root zone and sustaining a high soil water potential to reduce plant stress (**Tiwari *et al.*, 1998; Zotarelli *et al.*, 2009**). Drought remains one of the major limiting factors for crop yields and productivity globally (**Valliyodan and Nguyen, 2006**).

Chlorophyll is essential for photosynthesis, and magnesium plays a critical role in various plant functions, significantly impacting plant growth and yield. Magnesium, as part of the chlorophyll molecule, is vital for photosynthetic reactions and carbohydrate production. Plants with inadequate magnesium or potassium (K) supply cannot maintain optimal photosynthesis, leading to the accumulation of light energy in the leaves (**Mengel and Kirkby, 2001**). While magnesium's primary function is as the central atom in chlorophyll, it is also involved in energy conservation and conversion (**Amtmann and Blatt, 2009**), protein synthesis, and as a cofactor in various enzymatic processes related to phosphorylation, dephosphorylation, and hydrolysis. Magnesium also acts as a structural stabilizer for various nucleotides (**Marschner, 1995; Merhaut, 2007**).

Mentha longifolia, a native plant found in various parts of Egypt, has recently attracted attention due to its potential for commercial cultivation as a therapeutic and aromatic crop. However, there has been little research on its water requirements, crop coefficient at different growth stages, and the application of magnesium chlorophyllin (Mg-Chl. This study aims to determine the water needs and crop coefficient of *Mentha longifolia* while exploring how the innovative Mg-Chl formula can enhance these parameters. By improving plant productivity and drought resistance, Mg-Chl formula (**El-Tayeb, 2019**) offers a promising solution for large-scale desert cultivation in Egypt.

2. Material and Methods

A field experiment was conducted over two consecutive seasons, 2022 and 2023, at a private farm in the Al-Tour region, South Sinai Governorate, Egypt, located at latitude 28°17′56" N and longitude 33°37′45" E. The experiment aimed to evaluate the effects of irrigation periods and magnesium chlorophyllin (Mg-Chl) on the productivity of *Mentha longifolia* and its impact on water use efficiency and water conservation. The soil at the experimental site, classified as sandy loam, was analyzed according to **Page *et al.* (1984)** and contained 11.35% clay, 24.15% silt, and 64.50% sand. The chemical properties of the soil were measured, showing a pH of 7.24, electrical conductivity (EC) of 4.36 dS/m, and soluble anions of 2.10, 17.65, and 23.64 me/l for HCO_3^-, SO_4^{-2}, and Cl^-, respectively. Soluble cations were 8.23, 12.56, 20.20, and 2.40 me/l for Ca^{+2}, Mg^{+2}, Na^+, and K^+, respectively.

The irrigation water had a pH of 7.88, an EC of 0.77 dS/m, and contained soluble cations of 2.60, 3.86, 0.78, and 0.46 me/l for Ca^{+2}, Mg^{+2}, Na^+, and K^+, along with soluble anions of 1.44, 1.89, and 4.37 me/l for HCO_3^-, SO_4^{-2}, and Cl^-, respectively.

Each season, 25 m³/feddan of organic compost manure (containing 13.8% nitrogen, 0.86% phosphorus, 1.40% potassium, and 21.36% organic matter) was incorporated into the soil during preparation before planting. Table 1 presents the meteorological averages for the El-Tour region over the last ten years, as reported by **Desert Research Center (DRC, 2022).**

Table (4). Average meteorological data from ten years ago for the El-Tour area

Month	**Prc.**	**Tmp. mean**	**Tmp. Max.**	**Tmp. min.**	**Rel. hum.**	**Sunshine**	**Wind (m^2)**	**ETo**	**ETo**
	mm/m	C°	C°	C°	%	%	m/s	mm/m	mm/d
Jan.	10	14.8	18.7	10.8	42	79.6	3.6	95	3.1
Feb.	7	16.5	21.1	11.9	38.8	81.5	4.1	111	4.0
Mar.	45	19.5	24.5	14.6	37.2	78.6	4.6	164	5.3
April	0	23.3	28.4	18.2	32.1	78.9	5.3	219	7.3
May	0	28	33.5	22.5	27.1	83	5.4	273	8.8
June	0	30.4	35.9	25	26.8	90.7	6.2	311	10.4
July	0	32.1	37.1	27	30.5	91.7	6.5	326	10.5
Aug.	0	32.2	37.3	27.2	31	91.3	5.6	299	9.6
Sep.	0	31.5	37	26.1	37.9	89	5.1	240	8.0
Oct.	0	28.1	33.6	22.6	39	88.3	4	185	6.0
Nov.	0	21.5	25.7	17.4	41.1	84.8	3.9	122	4.1
Dec.	0	18.9	23.6	14.2	93.2	78.3	3.1	99	3.2
Total	62							2444	

ET0 = reference evapotranspiration

On March 5th of both seasons, 25 cm long *Mentha longifolia* rhizomes were planted in an open field under a drip irrigation system with a flow rate of 4 L/h. Plants were spaced 50 cm apart within each row, and rows were 1 meter apart. The experiment was arranged using a split-plot design. The main plot was assigned to three irrigation periods (every 2, 4, and 6 days), while the sub-plots included two different concentrations of magnesium chlorophyllin (Mg-Chl) at 0.5 g/L and 1 g/L, along with a control treatment (without Mg-Chl). The Mg-Chl formula was provided by Prof. Tarek A. El-Tayeb and used as received.

At the beginning of the experiment, irrigation was applied every two days for ten days to ensure seedling survival. Water management treatments were then initiated after the tenth day. The experiment experienced some rainfall in March, which was accounted for in the irrigation schedule. However, from April to July, the plants were exposed to extreme heat waves, with the most severe occurring in July 2023. As a result, four additional irrigations were applied during the first season and five during the second. The amount of irrigation water and the number of irrigations for each growth stage are detailed in Tables 2 and 3.

Table (2). Number of irrigations during the two seasons (2022 and 2023)

Irrigation periods every	First season							
	First cut				Second cut			
	Inat. stage	Dev. stage	Mad. stage	Total	Inat. stage	Dev. stage	Mad. stage	Total
2 days	18	25	25	68	15	23	22	60
4 days	11	15	14	40	8	14	12	34
6 days	9	10	11	30	5	10	9	24
	Second season							
2 days	18	25	25	68	15	23	22	60
4 days	11	16	14	41	8	15	12	35
6 days	9	10	11	30	5	10	9	24

Table (3). Quantities of applied water (m^3/fed) during the two seasons (2022 and 2023)

Irrigation periods every	First season							
	First cut				Second cut			
	Inat. stage	Dev. stage	Mad. stage	Total	Inat. stage	Dev. stage	Mad. stage	Total
2 days	1152	1600	1600	4352	960	1472	1408	3840
4 days	704	960	896	2560	512	896	768	2176
6 days	576	640	704	1920	320	640	576	1536
	Second season							
2 days	1152	1600	1600	4352	960	1472	1408	3840
4 days	704	1024	896	2623	512	896	768	2176
6 days	576	640	704	1920	320	640	576	1536

Mg-Chl treatments were applied to the plants using a hand-held sprayer until runoff occurred. The treatments were administered on days 21, 45, and 60 after planting and were repeated on the same days following the first harvest. Additionally, the recommended chemical fertilizers were applied according to the guidelines provided by **Swaefy *et al.* (2007)**. Standard agricultural practices for growing *Mentha longifolia* were followed as needed.

Harvesting took place twice per season, on July 15^{th} and November 15^{th}. Plants were cut 5 cm above the soil surface to measure the following parameters:

1. Plant Productivity and Components

At harvest, the following metrics were recorded: plant height (cm), fresh herb weight (g/m²), fresh herb weight (kg/feddan), dry herb weight (g/m²), and dry herb weight (kg/feddan).

2. Essential Oil and Composition

Essential oil percentage was determined using a Clevenger-style apparatus and hydrodistillation for three hours on air-dried herbs (**British Pharmacopoeia, 1963**). Essential oil per square meter (ml/m²) was calculated as: essential oil percentage × herb dry weight / m². Essential oil per feddan (L) was computed as: essential oil per square meter × 4000 m². Essential oil composition was analyzed using a GC-MS instrument at the Laboratory of Medicinal and Aromatic Plants, National Research Center, Egypt. Additionally, total chlorophyll content (SPAD) in the leaves of *M. longifolia* was measured using the method described by **Markwell *et al.* (1995).**

3. Actual Water Consumption of *M. longifolia*

Soil moisture content was measured using the gravimetric method at three depths: 0-20 cm, 20-40 cm, and 40-60 cm, before and after a 24-hour irrigation period. Water consumptive use was calculated using the equation (**Israelson and Hansen, 1962**):

$$CU= [(M2-M1) \times dp \times D] / 100$$

where:

CU = Consumptive use (mm), an estimate of actual evapotranspiration (ET) of the crop.

D = Depth (mm) of the irrigated soil.

dp = Bulk density (g/cm^3) of the soil in the relevant depth.

M2 = Soil moisture percentage (w/w) after maximum irrigation.

M1 = Soil moisture percentage (w/w) before the next irrigation.

Actual evapotranspiration (ETa) was calculated for each growth stage and for the entire season. Irrigation water use efficiency (WUE) was calculated as the ratio of herb fresh weight, dry weight, and oil yield (kg/feddan) to the total irrigation water volume applied per feddan (m^3/feddan) for the season (**Howell, 2006**). The crop coefficient for each growth stage was calculated according to **Allen *et al.* (1998).**

Data were analyzed using analysis of variance, and means were compared using the least significant difference (LSD) test at $P \leq 0.05$. Statistical analysis was performed using Version 9 of the statistical program (**Analytical Software, 2008**).

3. Results

3.1. Impact of Irrigation Periods, Magnesium Chlorophyllin, and Their Interaction on the Productivity of *Mentha longifolia* Plants

3.1.1. Growth and yield parameters

Based on the data from Figure 1 and Tables 4, 5, and 6, irrigation periods did not significantly impact plant height in either season, except for the first cut of the second season, where irrigation every two days was the most effective treatment. However, the irrigation periods did significantly affect the fresh herb weight per square meter, herb fresh weight per feddan, and dry herb weight per square meter and per feddan. Overall, irrigating every 4 days proved better than every 2 or 6 days for these parameters, with similar results observed in both cuts across both seasons. Specifically, irrigation every 4 days led to an average increase of 8.61% and 46.74% in fresh weight compared to irrigation every 2 and 6 days, respectively. For dry weight, the increases were 9.65% and 38.71% compared to the same treatments.

Additionally, the results in the same figure and tables show that spraying plants with Magnesium Chlorophyllin (Mg-Chl) significantly influenced plant height and both fresh and dry yields for both cuts in both seasons. The best treatment was spraying with 1 g/l of Mg-Chl, which resulted in average increases of 104.7% and 23.2% in fresh weight, and 127.5% and 27.9% in dry weight, compared to spraying with 0.5 g/l and the control (no Mg-Chl), respectively.

The data also suggest that spraying with Mg-Chl played an important role in enhancing plant height, especially when the irrigation period was extended. The most effective combination was irrigating every 4 days along with spraying 1 g/l of Mg-Chl. Moreover, the interaction between irrigation periods and Mg-Chl spraying had a significant effect on both fresh and dry yields in both growing seasons, with the combination of 4-day irrigation and 1 g/l Mg-Chl spray outperforming all other treatment combinations.

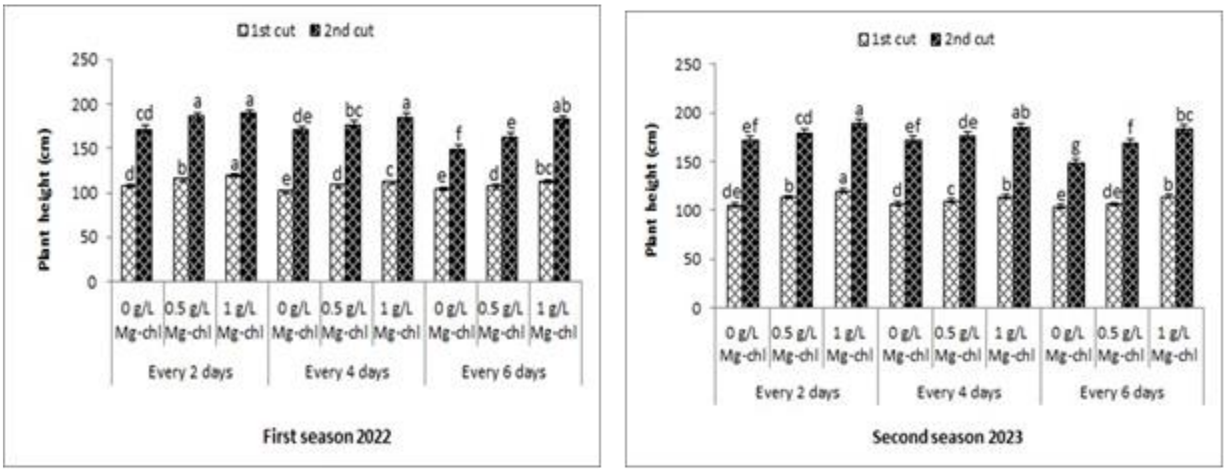

Fig. (1). Effect of Irrigation periods treatments on plant height of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

Table (4): Effect of irrigation period treatments on yield of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

Charact. / Irrig. periods	Herb fresh weight (g/m^2)		Herb fresh weight (kg/fed)		Herb dry weight (g/m^2)		Herb dry weight (kg/fed)	
	First season							
	1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut
Every 2 days	995.8	2091.6	3983.1	8366.5	227.6	477.8	910.2	1911.3
Every 4 days	1042.0	2200.6	4167.8	8802.3	231.7	560.8	926.9	2243.2
Every 6 days	992.6	1407.0	3970.4	5628.0	220.7	337.5	882.6	1349.9
L.S.D. at 5%	13.3	25.4	53.1	101.6	3.6	7.2	14.5	28.8
	Second season							
Every 2 days	1024.2	1761.5	4096.9	7045.9	230.7	399.6	922.9	1598.6
Every 4 days	1160.8	1975.9	4643.0	7903.5	246.0	426.2	984.1	1704.7
Every 6 days	870.7	1076.8	3482.7	4307.2	220.9	276.9	883.7	1107.5
L.S.D. at 5%	6.3	41.99	25.3	167.9	6.3	9.1	25.3	36.3

Table (5). Effect of Mg-Chlorophyllin treatments on yield of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

Charact. / Mg-Chlorophyllin	Herb fresh weight (g/m^2)		Herb fresh weight (kg/fed)		Herb dry weight (g/m^2)		Herb dry weight (kg/fed)	
	First season							
	1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut
Control	654.8	1199.2	2619.0	4797.0	143.5	306.9	573.8	1227.7
0.5 g/L	996.3	2083.9	3985.2	8335.6	225.8	483.2	903.2	1933.0
1 g/L	1379.3	2416.0	5517.1	9664.2	310.7	585.9	1242.7	2343.8
L.S.D. at 5%	10.3	25.1	41.4	100.4	2.3	6.6	9.2	26.3
	Second season							
Control	656.0	826.0	2623.8	3303.9	150.7	161.9	602.7	647.8
0.5 g/L	1119.2	1801.2	4476.8	7205.0	216.2	432.1	864.7	1728.5
1 g/L	1280.5	2186.9	5122.1	8747.7	330.8	508.6	1323.3	2034.4
L.S.D. at 5%	9.0	22.98	36.1	91.9	3.9	8.3	15.4	33.3

Overall, the combination of irrigating every 4 days and spraying plants with 1 g/L of Mg-Chl led to increases in fresh weight by 111.1%, 41.44%, and 23.2% compared to the control, spraying with 0.5 g/L, and spraying with 1 g/L of Mg-Chl under the 2-day irrigation schedule, respectively. For dry weight, the increases compared to the same treatments were 122.2%, 53.46%, and 28.1%, respectively. The same trend was observed in the second season.

Table (6). Effect of irrigation Periods, Mg-Chlorophyllin and their interaction treatments on yield of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

Charact. / Treatments		Herb fresh weight (g/m^2)		Herb fresh weight (kg/fed)		Herb dry weight (g/m^2)		Herb dry weight (kg/fed)	
		First season							
		1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut
Every 2 days	**Control**	682.0	1633.3	2728.1	6533.0	147.3	388.8	589.0	1555.1
	0.5 g/L Mg-Chl.	935.5	2267.4	3742.0	9069.0	235.6	502.5	942.4	2010.1
	1 g/L Mg -chl.	1369.8	2374.2	5479.2	9497.0	299.8	542.2	1199.3	2168.9
Every 4 days	**Control**	660.5	1327.8	2642.1	5311.0	143.9	381.2	575.6	1524.9
	0.5 g/L Mg-Chl.	1037.	2237.5	4150.3	8950.0	228.8	525.3	915.1	2101.1
	1 g/L Mg -chl.	1427.8	3036.5	5711.0	12146.0	322.5	775.9	1290.0	3103.7
Every 6 days	**Control**	620.7	636.6	2486.8	2547.0	139.2	150.8	556.9	603.1
	0.5 g/L Mg-Chl.	1015.8	1746.9	4063.4	6988.0	213.0	421.9	852.2	1687.7
	1 g/L Mg -chl.	1340.3	1837.5	5361.0	7350.0	309.7	439.7	1238.9	1758.8
L.S.D. at 5%		19.6	43.4	78.5	173.6	4.8	11.7	19.4	46.7
		Second season							
Every 2 days	**Control**	678.6	1195.4	2714.3	4782.0	156.6	265.5	626.5	1062.0
	0.5 g/L Mg-Chl.	1020.5	2027.7	4082.0	8111.0	196.5	452.5	785.8	1809.8
	1 g/L Mg -chl.	1373.6	2061.3	5494.4	8245.0	339.1	480.9	1356.6	1923.8
Every 4 days	**Control**	662.5	941.7	2649.9	3767.0	151.3	134.9	605.0	539.7
	0.5 g/L Mg-Chl.	1389.8	2038.5	5559.2	8154.0	219.6	480.7	878.6	1922.9
	1 g/L Mg -chl.	1430.0	2947.4	5720.0	11790.0	367.2	662.9	1468.8	2651.5
Every 6 days	**Control**	626.8	340.8	2507.2	1363.0	144.1	85.4	576.5	341.7
	0.5 g/L Mg-Chl.	947.3	1337.5	3789.2	5350.0	232.5	363.2	929.8	1452.8
	1 g/L Mg -chl.	1038.0	1552.0	4151.9	6208.0	286.2	382.0	1144.7	1527.9
L.S.D. at 5%		14.2	52.7	56.8	210.8	8.3	14.8	33.2	59.1

3.2. Effect of Irrigation Periods, Mg-Chlorophyllin, and Their Interaction on Essential Oil Productivity and Composition

3.2.1. Essential Oil Yield

The data in Tables 7, 8, and 9 clearly show that all irrigation period treatments had a significant impact on essential oil productivity. In some cases, there was no significant difference in essential oil percentage between irrigation every 4 and 6 days. However, irrigation every 6 days proved to be the most effective treatment overall. Additionally, irrigation every 4 days resulted in an essential oil yield increase of 3.32% in the first season and 32.83% in the second season compared to irrigation every 2 days.

The same tables also reveal that all concentrations of magnesium chlorophyllin (Mg-Chl) significantly improved oil percentage, oil yield per square meter, and per feddan compared to the control. Furthermore, higher Mg-Chl concentrations resulted in greater oil yields. Spraying plants with 1 g/L Mg-Chl was the most effective treatment, increasing oil yield by 136.5% in the first season and 149.32% in the second season compared to the control.

By analyzing the results from both seasons and examining the interaction between irrigation periods and Mg-Chl concentrations, it was found that increasing Mg-Chl concentrations under each irrigation schedule led to higher essential oil yields. Significant differences were observed across all interaction treatments, with the best combination being irrigation every 4 days along with 1 g/L Mg-Chl. This combination produced the highest essential oil yield per square meter and per feddan in both cuts of both seasons.

Table (7). Effect of irrigation periods treatments on essential oil of *Mentha longifolia* Plant during two cuts in the two seasons (2022 and 2023)

Charact. / Irrig. periods	Essential oil (%)		Essential oil yield/plant (ml)		Essential oil yield/fed (l)	
	First season					
	1st cut	**2nd cut**	**1st cut**	**2nd cut**	**1st cut**	**2nd cut**
Every 2 days	4.11	4.02	9.38	23.05	37.52	92.22
Every 4 days	4.53	4.57	10.82	22.68	43.27	90.71
Every 6 days	4.61	4.82	10.60	16.07	42.41	64.28
L.S.D. at 5%	0.13	0.05	0.22	0.63	0.88	2.50
	Second season					
Every 2 days	4.30	4.36	10.10	17.60	40.42	70.41
Every 4 days	4.64	4.84	11.88	24.90	47.53	99.58
Every 6 days	4.79	4.99	10.83	10.03	43.34	40.11
L.S.D. at 5%	0.07	0.05	0.28	0.29	1.14	1.18

Table (8). Effect of Mg-Chlorophyllin treatments on essential oil of *Mentha longifolia* Plant during two cuts in the two seasons (2022 and 2023)

Charact. / Mg-Chlorophyllin	Essential oil (%)		Essential oil yield/plant (ml)		Essential oil yield/fed (l)	
	First season					
	1st cut	**2nd cut**	**1st cut**	**2nd cut**	**1st cut**	**2nd cut**
Control	3.95	4.01	5.66	12.63	22.64	50.51
0.5 g/L	4.51	4.48	10.22	20.87	40.88	83.48
1 g/L	4.80	4.91	14.92	28.31	59.69	113.22
L.S.D. at 5%	0.13	0.09	0.32	0.74	1.27	2.95
	Second season					
Control	3.99	4.37	6.01	10.65	24.05	42.59
0.5 g/L	4.73	4.84	10.26	16.89	41.03	67.56
1 g/L	5.01	4.98	16.55	24.99	66.20	99.95
L.S.D. at 5%	0.08	0.08	0.37	0.33	1.46	1.31

Table (9). Effect of irrigation Periods, Mg-Chlorophyllin and their interaction treatments on essential oil of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

Treatments	Charact.	Essential oil (%)		Essential oil yield/plant (ml)		Essential oil yield/fed (l)	
		First season					
		1st cut	2nd cut	1st cut	2nd cut	1st cut	2nd cut
Every 2 days	**Control**	3.72	3.62	5.37	14.07	21.50	56.29
	0.5 g/L Mg-Chl.	4.09	4.03	8.72	20.82	34.86	83.28
	1 g/L Mg -chl.	4.53	4.42	14.05	34.27	56.18	137.09
Every 4 days	**Control**	3.99	4.10	5.86	17.29	23.44	69.14
	0.5 g/L Mg-Chl.	4.68	4.51	10.71	23.06	42.87	92.24
	1 g/L Mg -chl.	4.92	5.11	15.88	27.69	63.51	110.77
Every 6 days	**Control**	4.12	4.32	5.74	6.53	22.97	26.11
	0.5 g/L Mg-Chl.	4.76	4.91	11.23	18.73	44.89	74.93
	1 g/L Mg -chl.	4.95	5.22	14.84	22.95	59.37	91.81
L.S.D. at 5%		0.23	0.13	0.49	1.21	1.99	
		Second season					
Every 2 days	**Control**	3.80	4.13	5.74	10.97	22.97	43.90
	0.5 g/L Mg-Chl.	4.41	4.40	8.66	19.91	34.66	79.66
	1 g/L Mg -chl.	4.69	4.56	15.90	21.91	63.61	87.66
Every 4 days	**Control**	3.99	4.49	6.25	17.13	25.00	68.53
	0.5 g/L Mg-Chl.	4.79	4.94	10.51	23.75	42.06	94.99
	1 g/L Mg -chl.	5.14	5.10	18.88	33.81	75.52	135.22
Every 6 days	**Control**	4.19	4.49	6.04	3.84	24.17	15.35
	0.5 g/L Mg-Chl.	4.99	5.19	11.59	7.01	46.37	28.02
	1 g/L Mg -chl.	5.19	5.30	14.87	19.24	59.47	76.95
L.S.D. at 5%		0.13	0.09	0.59	0.55	2.35	2.18

3.2.2. Essential Oil Composition

Table 10 presents the effects of different interactions between irrigation periods and Mg-Chl treatments on the essential oil composition of *Mentha longifolia* plants. The GC-MS analysis identified 36 compounds in the essential oil, accounting for 98.89% to 99.74% of the total composition. Pulegone was the main component, ranging from 22.87% to 31.72%. Other significant components included 1,8-cineole (11.23%–17.64%), menthone (9.64%–14.73%), endo-borneol (9.07%–10.36%), α-terpineol (7.95%–10.31%), and α-pinene (5.70%–9.48%).

The interaction treatment involving irrigation every two days without Mg-Chl resulted in the highest percentage of pulegone (31.72%) compared to other treatments, while the lowest percentage (22.87%) was observed in the control treatment (no Mg-Chl) combined with irrigation every 6 days.

Table (10). Effect of irrigation Periods, Mg-Chlorophyllin and their interaction treatments on volatile oil composition of *Mentha longifolia* Plant

	Compound (%)	RT	Treatments			
			Irrigation every 2 days + Mg-Chl at 1 gL^{-1}	Irrigation every 2 days + without Mg-Chl	Irrigation every 4 days + Mg-Chl at 1 gL^{-1}	Irrigation every 4 days + without Mg-Chl
1	Phenylpentan-1-ol	5.13	0.64	-	-	-
2	2-Hexanamine (CAS)	5.20	0.39	-	-	0.17
3	à-Pinene,	6.42	5.70	8.59	9.19	9.48
4	Camphene	6.69	0.82	1.66	1.81	1.84
5	Sabinene	7.16	2.26	3.85	4.00	4.40
6	á-Myrcene	7.50	1.41	2.56	2.77	3.04
7	1,8-Cineole	8.37	17.64	11.49	11.23	11.76
8	Eucalyptol	8.49	-	2.58	2.21	2.02
9	Terpinene	9.04	0.08	-	0.18	0.15
10	trans Sabinene hydrate	9.15	0.22	0.59	0.53	0.80
11	à-Terpinolene	9.74	0.08	0.18	0.21	0.21
12	Linalool	9.86	0.22	0.65	0.66	0.73
13	1-Octanol	10.50	0.11	0.24	0.26	0.34
14	Sabinol	10.79	0.49	1.03	1.08	1.85
15	Verbenol	10.90	0.24	-	-	-
16	Menthone	11.02	14.26	14.44	14.73	9.64
17	Cyclohexanone	11.23	0.54	-	-	-
18	Endo-Borneol	11.41	9.67	9.13	9.07	10.36
19	Trans-3(10)-Caren-2-ol	11.61	-	0.14	-	-
20	l-4-Terpineol	11.70	0.23	0.58	0.68	0.70
21	Z-Citral	11.83	-	0.14	0.15	
22	à-Terpineol	11.96	8.89	8.01	7.95	10.31
23	Ketone	12.44	0.10	0.33	0.29	0.44
24	Pulegone	12.94	31.72	26.85	25.95	22.87
25	1-Methylethyl	13.29	-	0.33	0.19	0.34
26	6-Octen-1-ol	13.90	0.09	0.36	0.34	0.29
27	Nerol	14.01	0.08	0.36	0.19	0.40
28	Geraniol formate	14.47	0.41	1.38	1.39	1.70
29	4,6,6-Trimethyl	15.18	0.42	1.69	1.84	2.03
30	Caryophyllene	17.46	0.61	0.94	1.30	1.43
31	Germacrene-D	18.69	0.08	0.14	0.14	0.14
32	ç-Muurolene	19.31	-	0.14	0.16	0.16
33	Caryophyllene oxide	20.58	0.15	0.44	0.45	0.54
34	Veridiflorol	21.25	0.68	-	-	-
35	Trans-á-Ionon-5,6-Epoxide	21.33	0.37	-	-	-
36	Naphthalene	21.66	0.29	0.90	0.79	0.89
	Total		98.89	99.72	99.74	99.03

According to Figure 2, irrigation periods did not significantly affect the total chlorophyll content in *Mentha* plants during the first cut of both seasons. The best treatment for the first cut of the first season was irrigation every 2 days, while irrigating every 4 days was most effective for the second cut in both seasons. Spraying with Mg-Chlorophyllin (Mg-Chl) had a significant impact on total chlorophyll content in both cuts of both seasons. The most effective combination was irrigation every 4 days along with spraying 1 g/L Mg-Chl, which outperformed other treatments in both cuts across both seasons.

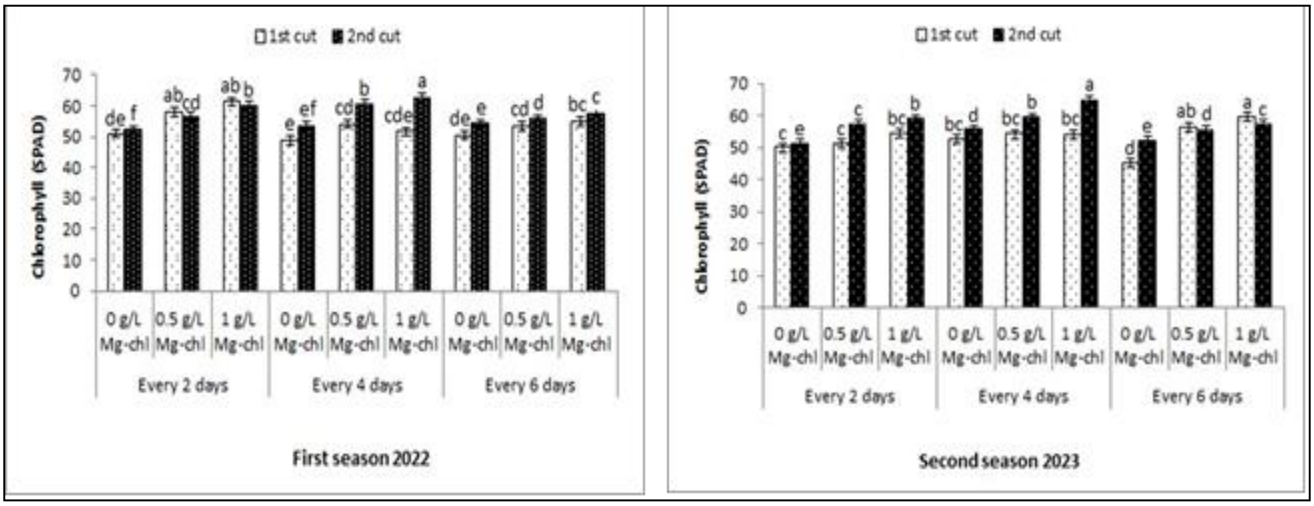

Fig. (2). Effect of irrigation period, Mg-Chlorophyllin and its interaction treatments on total chlorophyll of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

3.3. Effect of Irrigation Periods, Mg-Chlorophyllin, and Their Interaction on Water Parameters of *Mentha longifolia* Plants

3.3.1. Total Actual Evapotranspiration (mm/season)

Table 11 shows that water consumption increased as the plant growth stages advanced. Shorter irrigation periods resulted in higher amounts of water added and consumed, while extending the irrigation period led to a reduction in water consumption. On average, water usage decreased by 2641.52 m^3 and 3722.67 m^3 when irrigating every 4 days and 6 days, respectively, compared to the control treatment (irrigating every 2 days). Spraying with magnesium chlorophyllin (Mg-Chl) also reduced actual water consumption by an average of 1% to 3% at concentrations of 0.5 g/L and 1 g/L, respectively.

The combined effect of irrigation periods and spraying with magnesium chlorophyllin played a key role in helping the plants cope with stress and use water more efficiently. Spraying at a concentration of 1 g/L with an irrigation period of 6 days reduced average water consumption by 52% and 53% in the first and second seasons, respectively. Similarly, with an irrigation period of 4 days, water consumption decreased by 36% and 37% for both seasons.

3.3.2. Crop Coefficient

Table 12 shows that the length of the irrigation period had a clear impact on the crop coefficient, with longer preiods leading to a higher crop coefficient. Spraying with magnesium chlorophyllin slightly reduced the crop coefficient, and this reduction increased with higher spray concentrations. When studying the interaction between irrigation periods and magnesium chlorophyllin, it was evident that longer periods increased the crop coefficient. However, spraying with magnesium chlorophyllin decreased the crop coefficient, with the most significant reduction observed at a concentration of 1 g/L compared to the control for the same irrigation period. The average crop coefficient (Kc) for both seasons across different growth stages ranged from 0.95 for the initial stage, 0.92 for the development stage, and 0.96 for the middle stage.

Table (11). Effect of irrigation Periods, Mg-Chlorophyllin and their interaction treatments on actual water use (m^3/fed) of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

Irrigation periods	Mg-Chl.	First Season							
		Frist cut				Second cut			
		Inat.	Dvel.	Mad.	Total	Inat.	Dvel	Mad.	Total
2 days	control	1056.95	1230.96	1348.87	3636.78	878.91	1296.97	1308.86	3484.74
	0.5g/l	1043.80	1211.71	1341.23	3596.74	862.75	1279.81	1290.46	3433.02
	1g/l	1029.71	1193.50	1324.13	3547.34	858.11	1258.74	1269.19	3386.04
4 days	control	689.83	941.62	964.09	2595.54	489.45	845.58	759.70	2094.73
	0.5g/l	679.69	929.41	850.02	2459.12	480.34	841.12	752.49	2073.95
	1g/l	677.80	912.31	843.11	2433.22	469.21	828.30	749.27	2046.78
6 days	control	572.77	635.42	698.06	1906.25	317.61	639.77	573.41	1530.79
	0.5g/l	570.51	628.30	695.03	1893.84	314.11	636.42	572.09	1522.62
	1g/l	568.34	626.16	691.10	1885.6	311.04	634.11	568.10	1513.25
		Second season							
2 days	control	1018.78	1207.67	1402.80	3629.25	890.78	1304.56	1341.86	3537.2
	0.5g/l	996.62	1189.25	1389.62	3575.49	866.45	1289.80	1290.73	3446.98
	1g/l	980.40	1171.12	1368.21	3519.73	849.11	1268.35	1279.15	3396.61
4 days	control	690.22	1012.23	866.98	2569.43	492.37	867.79	735.89	2096.05
	0.5g/l	679.12	1003.05	859.34	2541.51	485.12	862.42	733.40	2080.94
	1g/l	671.04	999.12	856.02	2526.18	479.03	854.14	728.13	2061.3
6 days	control	572.06	638.92	698.45	1909.43	319.45	639.95	571.97	1531.37
	0.5g/l	570.11	637.34	689.10	1896.55	316.12	636.41	567.51	1520.04
	1g/l	566.08	634.07	686.04	1886.19	315.02	634.01	566.01	1515.04

Table (12). Effect of irrigation Periods, Mg-Chlorophyllin and their interaction treatments on Crop coefficient (Kc) of *Mentha longifolia* Plant during the two seasons (2022 and 2023)

Irrigation period	Mg-Chl.	First Season					
		First cut			Second cut		
		Inat.	Dvel.	Mad.	Inat.	Dvel.	Mad.
2 days	control	0.92	0.78	0.84	0.92	0.88	0.93
	0.5g/l	0.91	0.76	0.84	0.90	0.87	0.92
	1g/l	0.98	0.75	0.83	0.89	0.86	0.90
4 days	control	0.98	0.98	1.08	0.96	0.94	0.99
	0.5g/l	0.96	0.97	0.95	0.94	0.94	0.98
	1g/l	0.96	0.95	0.95	0.92	0.92	0.98
6 days	control	0.99	0.99	0.99	0.99	0.90	1.0
	0.5g/l	0.99	0.98	0.98	0.98	0.89	0.99
	1g/l	0.99	0.98	0.98	0.97	0.89	0.99
		Second Season					
2 days	control	0.88	0.75	0.88	0.93	0.88	0.95
	0.5g/l	0.87	0.74	0.87	0.90	0.88	0.92
	1g/l	0.85	0.73	0.86	0.88	0.86	0.91
4 days	control	0.98	0.99	0.97	0.96	0.97	0.96
	0.5g/l	0.96	0.98	0.96	0.95	0.96	0.95
	1g/l	0.95	0.98	0.96	0.94	0.95	0.95
6 days	control	0.99	1.0	0.99	1.0	1.0	0.99
	0.5g/l	0.99	1.0	0.98	0.98	0.99	0.99
	1g/l	0.98	0.99	0.97	0.98	0.99	0.98

3.3.3. Water Use Efficiency (WUE)

The effect of irrigation periods on water use efficiency (WUE) is shown in Tables 12, 13, and 14. As the amount of water applied decreased, WUE increased, and conversely, shorter irrigation periods led to lower efficiency. Spraying with Mg-Chlorophyllin (Mg-Chl) significantly improved WUE, with higher spray concentrations resulting in greater efficiency. The best treatment was spraying with 1 g/L of Mg-Chl, which increased WUE by 121.4% and 24% compared to the control and the 0.5 g/L treatment, respectively, in the first season. In the second season, WUE increased by 143.3 % and 18.9 % compared to the same treatments, respectively.

Table (12). Effect of irrigation periods on water use efficiency (WUE) of fresh, dry and oil yield during the two seasons (2022-2023)

Charact. / Irrigation periods	WUE of Fresh yield (kg/m^3)	WUE of Dry yield (kg/m^3)	WUE of Oil yield (l/m^3)
	First season		
2 days	1.5075	0.3444	0.0158
4 days	2.7386	0.6694	0.0283
6 days	2.7773	0.6460	0.0309
L.S.D. at 5%	0.0247	0.0101	0.0007
	Second season		
2 days	1.3602	0.3078	0.0135
4 days	2.6144	0.5603	0.0307
6 days	2.2540	0.5761	0.0241
L.S.D. at 5%	0.0345	0.0055	0.0006

Table (13). Effect of Mg-Chlorophyllin treatments on water use efficiency (WUE) of fresh, dry and oil yield during the two seasons (2022-2023)

Charact. / Mg-Chlorophyllin	WUE of Fresh yield (kg/m^3)	WUE of Dry yield (kg/m^3)	WUE of Oil yield (l/m^3)
	First season		
Control	1.4221	0.3470	0.0144
0.5 g/l	2.5092	0.5774	0.0259
1 g/l	3.0922	0.7354	0.0347
L.S.D. at 5%	0.0286	0.0052	0.0005
	Second season		
Control	1.1240	0.2368	0.010
0.5 g/l	2.3301	0.5300	0.021
1 g/l	2.7745	0.6774	0.034
L.S.D. at 5%	0.0205	0.0049	0.0004

Table (14). Effect of irrigation periods, Mg- chlorophyllin and their interaction treatments on water use efficiency (WUE) of fresh, dry and oil yield during the two seasons (2022-2023)

Treatments \ Charact.		WUE of Fresh yield (kg/m^3)	WUE of Dry yield (kg/m^3)	WUE of Oil yield (l/m^3)
		First Season		
Every 2 days	**Control**	1.1305	0.2617	0.0095
	0.5 g/L Mg-Chl.	1.5639	0.3604	0.0144
	1 g/L Mg -chl.	1.8281	0.4111	0.0236
Every 4 days	**Control**	1.6793	0.4435	0.0195
	0.5 g/L Mg-Chl.	2.7661	0.6369	0.0285
	1 g/L Mg -chl.	3.7705	0.9277	0.0368
Every 6 days	**Control**	1.4564	0.3356	0.0142
	0.5 g/L Mg-Chl.	3.1976	0.7349	0.0347
	1 g/L Mg -chl.	3.6780	0.8674	0.0437
L.S.D. at 5%		0.0495	0.0124	0.0009
		Second season		
Every 2 days	**Control**	0.9150	0.2061	0.0082
	0.5 g/L Mg-Chl.	1.4884	0.3169	0.0140
	1 g/L Mg -chl.	1.6772	0.4004	0.0185
Every 4 days	**Control**	1.3371	0.2385	0.0195
	0.5 g/L Mg-Chl.	2.8575	0.5838	0.0286
	1 g/L Mg -chl.	3.6486	0.8586	0.0439
Every 6 days	**Control**	1.1199	0.2657	0.0114
	0.5 g/L Mg-Chl.	2.6444	0.6894	0.0215
	1 g/L Mg -chl.	2.9977	0.7733	0.0395
L.S.D. at 5%		0.0355	0.0086	0.0008

Examining the interaction between irrigation periods and magnesium chlorophyllin (Mg-Chl) treatments revealed a significant impact on water use efficiency. The best treatment in both seasons was irrigating every 4 days combined with spraying 2 g/L of Mg-Chl, which resulted in an increase in water use efficiency of 236.3% and 300% compared to the control treatment with irrigation every 2 days, for the first and second seasons, respectively.

4. Discussion

Irrigation, along with the appropriate amount of water based on the plant's needs, is one of the key factors influencing agricultural production and crop quality. The challenge of managing high-quality water has become increasingly important in Egypt, especially with the growing issue of water scarcity and the adverse effects of climate change. **Saif *et al.* (2003)** highlighted that when sufficient moisture is available, the metabolic processes in plant cells are optimized, leading to enhanced efficiency in nutrient absorption.

The findings of this study showed that all irrigation treatments significantly influenced the growth parameters of *Mentha longifolia* plants, including plant height, fresh herb weight, dry herb weight, and essential oil yield. Irrigation every four days proved to be the most effective, followed by irrigation every two days, when compared to irrigation every six days. These results are consistent with previous studies conducted by **Tabrizi *et al.* (2011)** and **Bahreininejad *et al.* (2013)** on Thymus sp., **Hanafy *et al.* (2018)** on rosemary, **Abdel-Kader *et al.* (2014)** on lemongrass, **Khorasaninejad *et al.* (2011)** and **Hashem (2024)** on mint, and **Farzad *et al.* (2016)** on oregano.

Irrigation every 4 days led to the highest fresh herb weight and dry weight compared to irrigation every 2 or 6 days. Table 4 highlights that in the first season, irrigation every 4 days increased fresh herb yield by 8.6 % compared to irrigation every 2 days, and by 46.7% compared to irrigation every 6 days. Similarly, dry herb weight saw a significant increase, with irrigation every 4 days resulting in 9.65% and 38.7% higher yields compared to irrigation every 2 and 6 days, respectively.

The essential oil yield followed a similar trend, as shown in Table 7. Plants irrigated every 4 days produced higher essential oil yields per feddan than those irrigated every 2 days or every 6 days. In the second season, irrigation every 4 days increased essential oil yield by 17.5% compared to every 2 days, and by a significant 32.8% compared to every 6 days. These results suggest that extending the irrigation period beyond 4 days significantly reduces both plant productivity and essential oil yield, while more frequent irrigation (every 2 days) does not provide additional benefits and may lead to unnecessary water use. The increase in *M. longifolia* productivity with irrigation every four days may be attributed to the consistent water distribution, which allows the roots to expand both vertically and horizontally, resulting in a strong root system capable of absorbing the maximum amount of available water and nutrients.

Moreover, reduced photosynthesis, changes in canopy structure, or decreased turgor pressure which inhibits cell expansion and accelerates leaf senescence may explain the decline in fresh and dry herb yields with longer watering periods (**Shao *et al.*, 2008; Farooq *et al.*, 2009**). **Leithy *et al.* (2006)** suggested that reduced photosynthesis is associated with slower plant growth due to a decrease in stomatal conductance. According to **Jaleel *et al.* (2009),** leaf area expansion is vital for photosynthesis and dry herb production, as a smaller leaf area limits the plant's ability to capture light, thereby reducing the rate of photosynthesis **(Khalid, 2006)**.

Our study also showed that water consumption increased with plant age, and the applied water quantities significantly raised the actual water use. These findings align with those of **Abdel-Ghany and Abd El-Aleem (2020)** on *Pelargonium graveolens,* **Abd El-Ghany *et al.* (2017)** on fenugreek, and **El-Boraie *et al.* (2009)** on peanut plants.

Furthermore, the period between irrigation sessions is a key factor in drip irrigation management, as it influences soil moisture levels, root distribution, and their capacity to extract water **(Assouline, 2002)**. **El-Hendawy *et al.* (2008)** and **Liu *et al.* (2013)** demonstrated that higher irrigation frequency increases both crop yield and water use efficiency (WUE).

The study of irrigation period effects revealed that water use efficiency (WUE) increased with longer irrigation periods due to reduced water application over the period. This aligns with the findings of **Abdel-Ghany and Zaky (2019)**, who reported that both grain and straw WUE in wheat improved with reduced water availability.

Additionally, data from both seasons confirmed that shorter irrigation periods or higher water application rates led to reduced WUE. These findings are consistent with those reported by **Abd-Elghany *et al.* (2017)** on fenugreek, **Behera *et al.* (2014)**, **Okwany *et al.* (2011), Serag El-Din and Mokhtar (2020),** and **Hashem (2024),** who noted that WUE in mint crops significantly improved under increased water deficit.

The application of Mg-Chl dramatically improved plant performance across all measured parameters, as evidenced in Tables 5 and 8. When applied at a concentration of 1 g/L, Mg-Chl significantly increased both the fresh and dry weight of *Mentha longifolia* plants, as well as their essential oil yield. For instance, Mg-Chl treatment at 1 g/L increased fresh weight by 111.1% and dry weight by 122.2% compared to untreated plants irrigated every 4 days (Table 6). This increase was observed consistently across both seasons and in both cuts of the plant.

Essential oil yield also saw a remarkable increase with Mg-Chl treatment. Plants sprayed with 1 g/L of Mg-Chl produced up to 136.5% more essential oil in the first season and 149.32% more in the second season compared to the control plants, as shown in Table 8. The combination of Mg-Chl and a 4-day irrigation period proved to be the most effective, leading to the highest yields in both fresh and dry herb weight as well as essential oil production.

In the study, the application of magnesium chlorophyllin (Mg-Chl) significantly improved water use efficiency (WUE) across all irrigation periods. Without Mg-Chl, the 4-day irrigation period produced the best results for plant growth and oil yield. However, with Mg-Chl application, particularly at 1 g/L, the efficiency of water consumption was optimized even at a 6-day irrigation period. This treatment enhanced crop parameters such as fresh and dry herb weights, as well as essential oil production, showing improvements over the results without Mg-Chl. The Mg-Chl treatment allowed for better water utilization, which compensated for the reduced watering frequency, making the 6-day period competitive with the 4-day schedule under standard conditions. Therefore, while the 4-day period was optimal without Mg-Chl, the application of Mg-Chl shifted the balance, allowing for greater efficiency and productivity even at a longer irrigation period.

This dramatic improvement in productivity and oil yield with Mg-Chl application suggests that this novel foliar treatment **(El-Tayeb, 2019)** enhances key physiological processes such as photosynthesis, water uptake, and secondary metabolite production. Mg-Chl likely improves the efficiency of chlorophyll function, thereby boosting photosynthetic capacity, especially under water-limited conditions, as shown by the lower water consumption and improved water use efficiency (WUE) reported in Table 11.

5. Conclusion

The application of magnesium chlorophyllin (Mg-Chl) and optimization of irrigation periods have demonstrated significant potential to enhance both water use efficiency (WUE) and the productivity of *Mentha longifolia* under arid conditions. The study revealed that while irrigation every 4 days without Mg-Chl produced the best results for fresh and dry herb weights as well as essential oil yield, the application of Mg-Chl (particularly at 1 g/L) further amplified these effects. Notably, Mg-Chl allowed for improved water efficiency even at a 6-day irrigation period, without compromising plant growth or oil production. This suggests that Mg-Chl can alleviate water stress and optimize water consumption, making longer irrigation periods feasible while maintaining high yields. These findings highlight the value of Mg-Chl as an innovative foliar treatment for improving crop performance and resource management, particularly in water-scarce environments. The results offer promising implications for sustainable agriculture and large-scale cultivation of medicinal and aromatic plants in arid regions like South Sinai, Egypt.

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